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IDA PAPER P-2766

ASSESSING ACQUISITION SCHEDULES FOR UNMANNED SPACECRAFT

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April 1993

Prepared for
Ballistic Missile Defense Organization

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UNCLASSIFIED

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1993

3. REPORT TYPE AND DATES COVERED
Final Report, Apr 1991 – Apr 1993

4. TITLE AND SUBTITLE
Assessing Acquisition Schedules for Unmanned Spacecraft

5. FUNDING NUMBERS
MDA 903 89C 0003
T-R2-597.18

6. AUTHOR(S)
Bruce R. Harmon, Neang I. Om

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311-1772

8. PERFORMING ORGANIZATION REPORT NUMBER
IDA Paper P-2766

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
BMDO/POE
Room 1E1037, The Pentagon
Washington, D.C. 20301

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12A. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12B. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The research documented in this report was initiated to provide methods for assessing the reasonableness of proposed acquisition schedules for space-based elements of proposed SDS architectures and for the software associated with both space-based and ground-based segments of these systems. The approach used in accomplishing this task was to: (1) review the relevant literature; (2) collect historical schedule and technical data on acquisition programs for unmanned spacecraft; (3) compile the data in consistent formats for use in data analyses and for comparison with future acquisition programs for space systems; and (4) analyze schedule intervals in the data, derive time-estimating relationships (TERs), and integrate the TERs into a schedule-assessment tool that spans the period from engineering development start through production. The primary technique in defining and testing TERs was linear regression analysis. In applying regression analysis, schedule interval lengths measured in months were treated as dependent variables and regressed against independent variables that were thought to influence the interval lengths. Multiple TERs are presented for three different schedule intervals, engineering development duration, manufacturing intervals for production spacecraft, and software development duration. The TERs are integrated and an example application is presented.

14. SUBJECT TERMS
Time-Estimating Relationships, Space Systems, Unmanned Spacecraft, Strategic Defense System, Acquisition, Linear Regression Analysis

15. NUMBER OF PAGES
144

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

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Distribution /		
Availability Codes		
Dist	Avail and / or Special	
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April 1993

INSTITUTE FOR DEFENSE ANALYSES

Contract MDA 903 89 C 0003

Task T-R2-597.18

PREFACE

This paper was prepared by the Institute for Defense Analyses (IDA) for the Ballistic Missile Defense Organization (BMDO) under a task entitled "Methods to Assess Schedules for the Strategic Defense System." The objective of the task was to provide methods for assessing the reasonableness of proposed acquisition schedules for elements of proposed System architectures and the software associated with segments of these systems.

This work was reviewed within IDA by James Bui, Peter Kysar, and William Shafer.

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I. INTRODUCTION

A. BACKGROUND

Representatives of the Ballistic Missile Defense Organization (BMDO) are responsible for the review of acquisition programs for space-based systems constituting proposed Strategic Defense System (SDS) architectures. Part of this process involves the review of proposed acquisition schedules. The research documented in this report was initiated to provide BMDO personnel with methods for assessing the reasonableness of proposed acquisition schedules for elements of proposed SDS architectures. The methods are used specifically for space-based elements of the SDS and for both space- and ground-based software associated with those systems. Such methods should reproduce schedules typical of analogous historical systems while accounting for schedule variations associated with differing technical or program characteristics.

B. APPROACH

This work follows on two previous studies [1 and 2] that examined tactical aircraft and air-launched missile acquisition schedules. The approach in many ways parallels that used for the previous studies. The approach used in accomplishing this task was to:

- Review the relevant literature.
- Collect historical schedule and technical data on acquisition program for unmanned spacecraft.
- Compile the data in consistent formats for use in data analyses and for comparison with future acquisition programs for space systems.
- Analyze schedule interval data, derive time-estimating relationships (TERs), and integrate the TERs into a schedule-assessment tool that spans the period from engineering development start through early production.

Because proposed SDS space-based systems are to be built at higher rates than any space system acquired in the past, the schedule effects of large production buys are also of interest.

The examination of historical data is the appropriate starting point for the development of a schedule-assessment tool. We collected data on 26 unmanned spacecraft programs. Included are most of the important operational Department of Defense (DoD) spacecraft from the late-1960s to the present. We define an operational spacecraft as any spacecraft designed to be a part of a spacecraft constellation that has a continuous and long-term mission. Also included are four commercial communications spacecraft, and selected NASA and DoD experimental and scientific unmanned spacecraft. We collected data on spacecraft manufacturing intervals for nine spacecraft production programs. We also collected schedule data on space-system software projects. These data were collected at the computer software configuration item (CSCI) level for both space-based and ground-based segments of space systems.

The technique used in defining and testing the TERs was linear regression analysis. The data for the analyses are in Chapter III. Of relevance are not only schedule data but also the program and technical parameters to which the length of schedule intervals may be related. In applying regression analysis, schedule interval lengths measured in months were treated as the dependent variable and regressed against independent variables that were thought to be correlated with this interval. The adequacy of the regression models was tested using standard measures of statistical significance and model fit.

The original approach in the analysis of development schedule data was to decompose development program schedules into multiple schedule periods or intervals for which estimating relationships might be found. Although this approach was successful in IDA's previous schedule-estimating studies, it did not prove so for space systems. Apparently schedule intervals within spacecraft development programs are not characterized consistently enough within the data to yield satisfactory estimating relationships. The alternative approach was to estimate the overall development schedule; as the number of data points for the overall schedule is relatively large, this allowed us to use various data segmentation schemes, yielding a set of estimating relationships with overlapping domains.

One issue in defining the spacecraft development interval to be analyzed was which milestone should mark the end of development. In previous unmanned spacecraft schedule studies (reviewed in Chapter II), the first launch of the spacecraft marks the end of development. In our early analysis of the data, we found that the first-launch date could be misleading in defining the end of major development activities. In some cases, the first flight-model spacecraft would be tested and delivered only to be stored for an extended period awaiting the availability of launch resources. This situation was particularly common in the wake of the Challenger accident in 1986. In our analyses, we chose the delivery of the first flight-model spacecraft as the milestone marking the end of development. Thus the schedule interval on which we concentrated our analyses was the time from full-scale development (FSD) start (sometimes referred to as development authority to proceed or ATP) to the delivery of the first flight-model spacecraft. This interval corresponds roughly to phase C/D for the NASA programs.

In addition, we developed TERs for spacecraft manufacturing and software development milestone intervals. We examined the relationship between manufacturing milestone intervals, development time, and cumulative quantity using data describing nine production programs. For software, the development length at the CSCI level is the unit of analysis. Documentation of the development of all TERs is presented in Chapter IV.

In Chapter V, we describe an example application of the TERs presented in Chapter IV. For this application, we chose a hypothetical Brilliant Eyes class sensor spacecraft. In our example, we integrate development schedule-estimating relationships with those for manufacturing. Software development schedule intervals are incorporated into the overall acquisition schedule.

II. PAST STUDIES

The literature contains few previous studies related to our topic. The major contributions are contained in the following four studies: Planning Research Corporation's (PRC's) "Unmanned Spacecraft/Carriers Time Estimating Relationships" (1981) [3], PRC's "NASA Cost Model (NASCOM) Data Base" (1990) [4], Tecolote's "Schedule Assessment Data Base Development" (1988) [5], and Greer and Moses' "Estimating and Controlling the Cost of Extending Technology" (1989) [6]. We discuss the four studies in the order of their generality. The NASCOM study examined costs and schedules for various types of space-related equipment, including NASA, DoD, and commercial unmanned spacecraft, manned spacecraft, launch vehicles and space-based scientific instruments. The earlier PRC study was concerned with the development phase of unmanned spacecraft/carriers representing NASA and DoD programs. Greer and Moses' research focused on technology advance and cost, but included an analysis of development times for 18 satellite programs whose missions include communications, surveillance, and navigation. The Tecolote study addressed the entire acquisition cycle for a small group of DoD and a single NASA operational satellite.

A. NASCOM DATA BASE: TIME-ESTIMATING RELATIONSHIPS

The NASCOM Data Base study was performed by Planning Research Corporation for the Engineering Cost Group of the Marshall Space Flight Center. In this study, time-estimating relationships are presented for four equipment types: manned spacecraft, unmanned spacecraft, launch vehicles, and scientific instruments. The following rules and assumptions are made for all the TERs: the equation form is $Y = ax^b$, where a is the intercept, b is the slope, and x is the independent variable. The independent variable is equipment dry weight (WT(D)). Engine weight is included in the launch vehicle equations. Ordinary least squares technique is used to derive parameter estimates. The time intervals are defined as authority to proceed (ATP) or contract go-ahead to first manned launch for manned spacecraft, delivery of the first flight unit for launch vehicles, and first launch for unmanned spacecraft. Scientific instrument schedule intervals are measured from development start through delivery to the integrating contractor. Because unmanned spacecraft and the instruments associated with them are the items of interest to us, we summarize the results for these equipment types in the following subsections.

1. Unmanned Spacecraft

For unmanned spacecraft, two TERs are presented; one for all mission types (DoD and NASA), and one for NASA missions only. Results for the NASA missions show a better fit.

In the TER for all mission types, spacecraft dry weight (WT(D)) was regressed against schedule duration from ATP to first launch. The equation is:

$$\text{Time in months} = 8.173\,WT(D)^{.238},$$
$$N = 18 \qquad R^2 = .57,$$

where N is the number of data points and R^2 is the coefficient of determination. R^2 describes the amount of variation explained by the model as a proportion of the total variation in the data. The exponent on WT(D) is restricted to .238.

In the TER for the NASA missions only, the same specification was used. The equation is:

$$\text{Time} = 9.057\,WT(D)^{.238},$$
$$N = 13 \qquad R^2 = .72.$$

The differences in the intercept coefficients indicate that NASA missions take longer to first launch than other missions.

2. Scientific Instruments

Four TERs are presented for scientific instruments. They are grouped by technical classification: spectroheliograph, pryheliometer, mass measurement, photometer, and spectrometer. TERs for both pryheliometers and spectroheliographs have good correlation values, but TERs for mass measurement, photometers, and spectrometers provide less confidence in prediction. This lack of confidence is probably a function of the wider range of applications and overall mission types for these instruments and the number of data points in the sample. The TERs are:

- Spectroheliograph:

$$\text{Time} = 16{,}971\,WT(D)^{.247},$$
$$N = 6 \qquad R^2 = .82;$$

- Pryheliometer:

$$\text{Time} = 8.830\text{WT(D)}^{.456},$$
$$N = 3 \qquad R^2 = .93;$$

- Mass Measurement:

$$\text{Time} = 7.825\text{WT(D)}^{.520},$$
$$N = 10 \qquad R^2 = .58;$$

- Photometer:

$$\text{Time} = 18.462\text{WT(D)}^{.200},$$
$$N = 16 \qquad R^2 = .44;$$

- Spectrometer:

$$\text{Time} = 13.921\text{WT(D)}^{.268},$$
$$N = 18 \qquad R^2 = .59.$$

B. PRC: TIME-ESTIMATING RELATIONSHIPS

In this study performed for NASA, 21 unmanned spacecraft program schedules were included in the analysis. The database was dominated by NASA programs; only two DoD programs were included. The report contains tables presenting schedule intervals, including test and launch dates in calendar year, time in months from launch, and technical characteristics for the 21 data points chosen. The schedule interval, the subject of the TERs in this study, is the program development time from ATP, which in most cases is contract award, to first launch. The single independent variable specified is spacecraft weight (W). Four versions of the TERs, all derived by linear regression, are presented.

The first TER was estimated using a database that included first-generation spacecraft programs and modification programs entailing radical design changes. The TER estimated using this database is designated T1, where:

$$T1 = 31.134\ W^{.055},$$
$$N = 21\ R^2 = .02.$$

The R^2 for the regression equation was only .02; weight explains very little of the variation in the data. The other TERs were estimated using data points that fall into the following categories: first generation/new programs (T2), advancing state-of-the-art/new technology programs (T3), and military programs (T4). Because there was no significant difference between the TERs for T1 and T2, and the slopes for T3 and T4 were unrealistic due to the small amount of data available, PRC recommended the T1 TER.

C. GREER AND MOSES: ESTIMATING AND CONTROLLING THE COST OF EXTENDING TECHNOLOGY

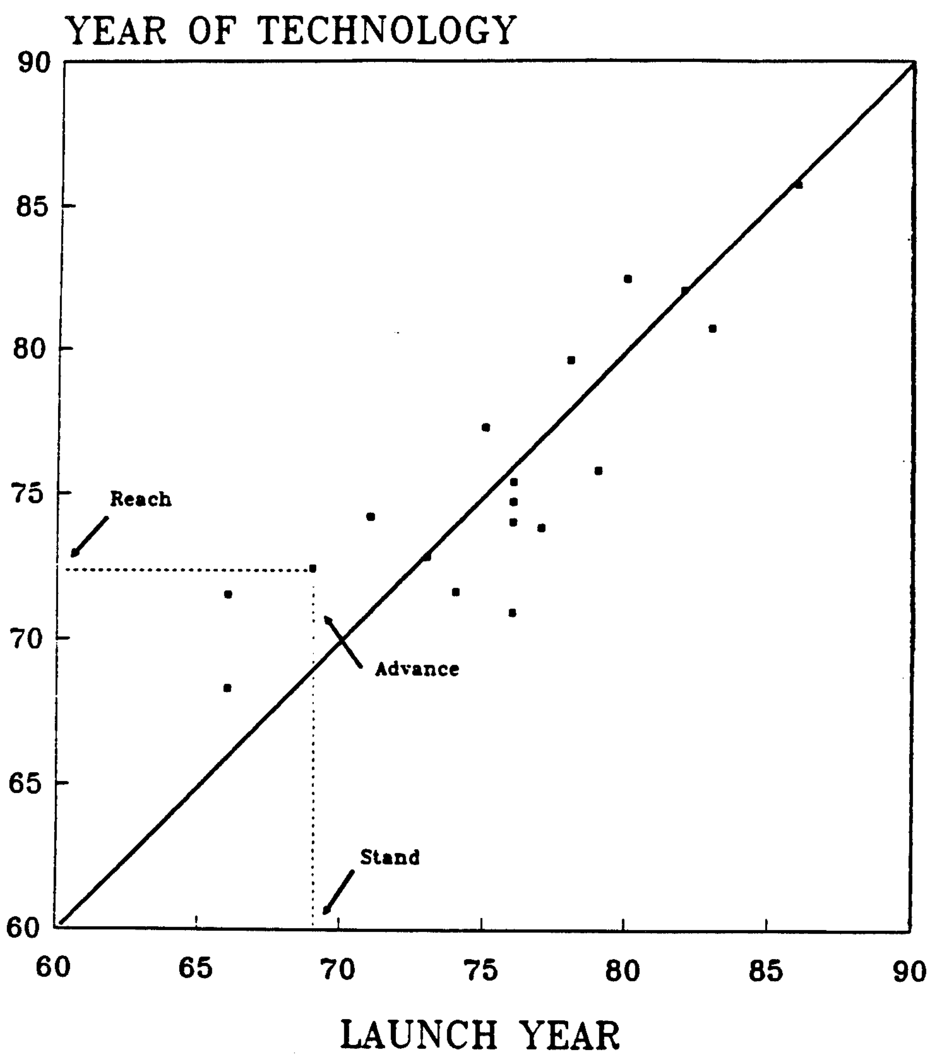
This study addressed how to measure the state of the art of satellite technology and technology extensions to assist in cost prediction and control. The study employed technical, schedule, and cost data from 18 satellite programs. The study expanded on previously presented methods for quantifying the incremental technological progress represented by a particular project. It formulated and tested the relationships between technology measures and development time and development costs, specified variance measures related to development cost, examined the relationships between the scope of the development phase (as characterized by development time) of a program and subsequent production cost, and introduced a series of relationships between technology and costs that can be used to estimate and control the cost of extending technology. Our primary interest in this study is on the estimating relationships for development time.

The year-of-technology approach combines numerous technology descriptions into a summary technology measure expressed in terms of time (years). For each of the 18 unmanned spacecraft used in the study, 84 technical characteristics were available. Of these, 17 were chosen by expert opinion as the best in describing the level of satellite technology. A principle components factor analysis was conducted to reduce the 17 variables to four sets of factor scores to be used as explanatory variables. The four factors are interpreted as technology indexes for mission requirements, orbital characteristics, electrical power, and environment. The launch year of the first unit of each satellite program was regressed against the four technology indexes to determine the year of technology. The overall model is significant at the .0001 level with an adjusted R^2 of .65; each factor is significant with positive coefficients, consistent with increasing values of the four technology descriptors that reflect increasing technology over time.

Using this framework, three technology measures were created for each individual satellite system: REACH, ADVANCE, and STAND. The predicted value (Ye) from the regression equation for an individual system represents the year of technology or state of the art (SOA) for the system and is labeled by Greer and Moses as REACH. Y, the actual year in which a satellite was first launched, represents where technology currently "stands" for that system; therefore, Y = STAND. If Y < Ye, the system was ahead of its time and

ADVANCE = Ye – Y. If Y > Ye, the system was behind the time trend and ADVANCE has a negative value. Greer and Moses suggest that the three technology measures be used to assist in cost prediction and control.

Figure II-1 presents a plot of year of launch (Y) versus year of technology (Ye) taken from [6]. Using the approach outlined above, the values for STAND, REACH, and ADVANCE for each system were determined. System H is highlighted in Figure II-1 to illustrate the calculations. It was actually launched in 1969 (STAND) but has a year-of-technology value (REACH) that falls between 1972 and 1973. Thus, it was three to four years ahead (ADVANCE) of the general trend in technology.



Source: Reference [6], p. 49.

Figure II-I. Year-of-Technology Plot

Two variables capture complexity. STAND measures the current state of technology at the time of project development; as the state of technology increases, the level of complexity increases. ADVANCE measures the increment in technology to be achieved by the development project. REACH is simply the sum of STAND and ADVANCE; therefore, it contains no additional information and was excluded from the analysis.

Two hypotheses were proposed in explaining the relationships among development cost, development time, and technological complexity. First, there is a direct relationship between development cost and the development task, measured in terms of technological complexity, H1: Development Cost = f (+STAND, +ADVANCE). Second, there is an intervening variable between development cost and technological complexity—development time. Complexity affects time, and time affects cost.

The time required for the development task is hypothesized to be a positive function of technological complexity, H2: Development Time = f (+STAND, +ADVANCE). The resulting model is as follows:

$$\text{Development Time} = -239 + 3.70(\text{STAND}) + 2.03(\text{ADVANCE}),$$

$$N=18 \qquad R^2 = .75.$$

Both STAND and ADVANCE have positive coefficients statistically significant at .001 and .030 probability levels. The actual time required to complete a development project is a function of both the level of technological complexity at which the task is taking place and the additional increment in technology to be achieved.

The regression equation defining the relationship between development time and development cost is:

$$\text{Development Cost} = 52{,}841 + 2350(\text{Predicted Time}) + 10{,}482(\text{Residual Time})$$

$$N=18 \qquad R^2 = .49$$

where the predicted time from the development time equation is defined as the "natural" development time, and Residual Time = Actual Time – Predicted Time for a given development. The regression analysis shows the coefficients to be significant at the .074 and .002 levels.

D. TECOLOTE: SCHEDULE ASSESSMENT

The Tecolote report presents detailed chronologies associated with five major DoD and one NASA spacecraft program: the Defense Satellite Communications System (DSCS), the Defense Meteorological Satellite Program (DMSP), the Fleet Satellite Communications (FLTSAT) system, the Global Positioning System (GPS), and the Defense Support Program (DSP), the Tracking and Data Relay Satellite System (TDRSS). Schedule and technical data for historical spacecraft systems and descriptions of delays that transpired between major milestones were documented. No estimating relationships were presented.

E. SUMMARY

The two PRC studies were similar in that they present weight-based models for predicting development times. Using weight as a schedule driver has its disadvantages. Weight is considered by some to be a poor proxy for technological complexity [7]. The weight-based TERs also fall short in terms of model fit; the highest R^2 reported is .72. The Greer and Moses study was fundamentally different from the others because development time was modeled explicitly as a function of technological complexity. Unfortunately, the Greer and Moses approach was geared more to cost and schedule monitoring once a program is underway, as opposed to assessing a program before it starts. In order to accurately estimate STAND, ADVANCE, and Residual Time, we must first have an accurate estimate of the system's first launch date. In essence, we are using measures derived assuming a known schedule to estimate that schedule. Their approach also requires a great deal of other information to make an estimate (data on all 17 technology variables are needed to derive the factor scores), and the model fit still leaves something to be desired. All three studies have the drawback that they use first-launch as a proxy for development end; as we pointed out in Chapter I, first launch may be an inconsistent metric for development end. The Tecolote study provides schedule information in much more detail than the other studies. Although it presents no estimating relationships, it still has considerable value as a data reference for assessing proposed schedules by analogy.

III. DATA COLLECTION AND PRESENTATION

A. SCOPE OF DATA COLLECTION

We collected data in some detail for 26 unmanned spacecraft programs. Our primary interest was in Department of Defense (DoD) spacecraft; commercial and NASA spacecraft were added to the database to increase the number of data points available for analysis and add breadth in terms of spacecraft characteristics. In the data collection effort, emphasis was placed upon the development phase of the acquisition cycle. Our primary concern was engineering development program milestones and the schedule intervals derived from them. Some emphasis was placed on collecting manufacturing milestone data. Software data were collected at the computer software configuration item (CSCI) level from existing space-system software databases; data were included for CSCIs based both on the ground and in space. Schedule intervals in the concept exploration phase and the demonstration and validation phase prior to engineering development are often highly dependent upon factors exogenous to the development process and were therefore not emphasized in our data collection or analyses.

We also collected data on spacecraft physical and performance characteristics and program attributes to which schedule intervals may be related. We depended on unclassified sources of information wherever possible.

This chapter presents summary data on program and spacecraft characteristics, spacecraft development program schedules, manufacturing schedules, and space-system software characteristics and schedules. For purposes of data presentation, we grouped the programs into three categories: DoD sensor/navigation, NASA scientific/experimental, and operational communications. Sensor spacecraft are spacecraft whose primary payload is a sensor or scientific instrument package; navigation spacecraft are spacecraft whose primary payload provides signal information to assist users in navigation tasks. Navigation spacecraft include both versions of the Global Positioning System (GPS) spacecraft. The NASA scientific/experimental spacecraft include Earth-orbiting spacecraft and planetary probes. Operational communications spacecraft include DoD, commercial, and a single NASA program. We define an operational spacecraft as any spacecraft designed to be part of a spacecraft constellation having a continuous and ongoing mission. Operational spacecraft are characterized by series production, albeit in small numbers.

Appendix A presents more detailed development schedule data than provided here, and Appendix B provides program descriptions to help place program schedules into context.

B. PROGRAM AND SPACECRAFT CHARACTERISTICS

In general we collected program and technical data from secondary sources. The most important source was the Air Force Space Systems Division's (SSD's) Unmanned Spacecraft Cost Model database, editions five and six [8 and 9]. Other important data sources included PRC's NASCOM database [4] (NASA Earth-orbiting spacecraft), Aerospace Corporation's catalog of communications spacecraft [10] (commercial communications spacecraft), and the Jet Propulsion Laboratory's (JPL) Spacecraft and Probe databases [11] (planetary spacecraft).

Tables III-1, III-2, and III-3 present information characterizing eight DoD sensor/navigation spacecraft programs, nine NASA scientific/experimental spacecraft programs, and nine operational communications spacecraft programs. In each case, technical and program characteristics that might have an effect on schedule intervals were included. The definitions of the spacecraft characteristics are as follows:

- *Stabilization method.* Describes the method used for spacecraft attitude control. Spin-stabilized spacecraft are generally less complex than three-axis stabilized spacecraft.
- *Dry weight.* Total weight of spacecraft in pounds, excluding fuels, where the spacecraft includes the structure, interstage adapter, attitude control subsystem, thermal control subsystem, telemetry tracking command, communications payload and propulsion subsystem.
- *Beginning of life (BOL) power.* Peak electrical power in watts available at the beginning of spacecraft life. For planetary spacecraft, BOL power is measured at Earth.
- *End of life (EOL) power.* Peak electrical power in watts available at the end of the spacecraft's design life. For planetary spacecraft, this is the end of mission power.
- *Apogee.* Maximum altitude of the spacecraft in nautical miles in Earth orbit. Geosyncronous spacecraft have a circular orbit with an apogee of 19,300 nautical miles.
- *Perigee.* Minimum altitude of the spacecraft in nautical miles in Earth orbit.
- *Design life.* The mission duration in months for which the spacecraft was designed.

Table III-1. Characteristics for DoD Sensor/Navigation Spacecraft Programs

	Sensor Spacecraft						Navigation Spacecraft	
	Defense Meteorological Satellite Program Block 5D-1 (DMSP 5D-1)	Defense Meteorological Satellite Program Block 5D-2 (DMSP 5D-2)	Defense Support Program Spacecraft 1 (DSP 1)	Defense Support Program Spacecraft 5R and 6R (DSP 5R)	Defense Support Program Spacecraft 14 (DSP 14)	Air Force Space Test Program Mission P-72-2	Global Positioning System Block I (GPS I)	Global Positioning System Block II (GPS II)
Program Characteristics								
Development Agency	USAF/SSD	USAF/SSD	USAF/SSD	USAF/SSD	USAF/SSD	USAF/SSD	USAF/SSD	USAF/SSD
Prime Contractor	RCA	RCA	TRW	TRW	TRW	Rockwell	Rockwell	Rockwell
Development Approach	Prototype	Protoflight	Prototype	Protoflight	Protoflight	Protoflight	Prototype	Prototype
Development Start	Mar 72	Apr 75	Dec 66	Oct 78	Nov 81	Jul 72	Jun 74	Dec 80
Launch Vehicle(s)	Thor LV-2F	Atlas E	Titan IIC	Titan 34D-Transtage	Titan IV/ STS-IUS	Atlas F	Atlas E/F	Delta-II/STS
Mission	Meteorological	Meteorological	Surveillance/ Early Warning	Surveillance/ Early Warning	Surveillance/ Early Warning	Experimental Surveillance	Navigation	Navigation
Spacecraft Characteristics								
Stabilization Method	3-Axis	3-Axis	Spin	Spin	Spin	3-Axis	3-Axis	3-Axis
Dry Weight (lbs)	1,052	1,370	1,074	2,845	3,846	1,003	875	1,332
BOL Power (watts)	1,153	1,266	670	990	1,600	260	523	980
EOL Power (watts)	—	428	413	705	1,265	—	402	709
Apogee (nmi)	450	450	19,300	19,300	19,300	400	10,900	10,900
Perigee (nmi)	450	450	19,300	19,300	19,300	400	10,900	10,900
Design Life (months)	18	30	36	60	60	6	60	90

Note: Dashes denote that data were not available.

Table III-2. Characteristics for NASA Scientific/Experimental Spacecraft Programs

Characteristics	Earth Orbiting					Planetary			
	Application Explorer Mission-Heat Capacity Mapping Mission (AEM-HCMM)	Atmospheric Explorer C (AE-C)	High Energy Astronomy Observatory (HEAO)	Hubble Space Telescope (HST)	Spacecraft Charging at High Altitudes (SCATHA)	Mariner 5	Mariner 6	Mariner 10	Viking Orbiter
Program									
Development Center	Goddard	Goddard	Marshall	Marshall	Marshall	JPL	JPL	JPL	Langley
Prime Contractor	Boeing	RCA	TRW	Lockheed	Martin	JPL	JPL	Boeing	JPL
Development Approach	Protoflight	Protoflight	Protoflight	Protoflight	Protoflight	Prototype	Prototype	Prototype	Prototype
Development Start	Dec 74	Oct 71	May 72	Oct 77	Mar 76	Dec 65	Feb 66	Apr 71	Feb 70
Launch Vehicle	Scout D	Delta 2900	Atlas-Centaur	STS	Delta 2914	Atlas-Agena	Atlas-Agena	Atlas-Centaur	Titan IIIE-Centaur
Mission	Thermal Mapping	Atmospheric Research	Astrophysical Observation	Astronomical Observation	Spacecraft Charging Research	Venus Flyby	Mars Flyby	Venus/ Mercury Flyby	Mars Orbiter
Spacecraft									
Stabilization Method	3-Axis	3-Axis	3-Axis	3-Axis	Spin	3-Axis	3-Axis	3-Axis	3-Axis
Dry Weight (lbs)	185	780	2,602	19,462	1,194	515	909	1,043	1,976
BOL Power (watts)	180	170	1,085	4,000	290	430	830	490	1,400
EOL Power (watts)	—	140	—	—	—	200	475	381	620
Apogee (nmi)	348	2,321	246	320	23,355	N/A	N/A	N/A	N/A
Perigee (nmi)	301	83	232	320	14,880	N/A	N/A	N/A	N/A
Design Life (months)	12	12	6	180	12	6	—	12	4.7

Note: Dashes denote that data were not available; N/A means "not applicable."

Table III-3. Characteristics for Operational Communications Spacecraft Programs

Characteristics	DoD/NASA					Commercial			
	Defense Satellite Communications System Phase II (DSCS II)	Defense Satellite Communications System Phase III (DSCS III)	Fleet Satellite Communications (FLTSAT)	North Atlantic Treaty Organization Phase III (NATO III)	Tracking and Data Relay System Satellite (TDRSS)	International Telecommunications Satellite System IV (ISAT IV)	International Telecommunications Satellite System IVA (ISAT IVA)	International Telecommunications Satellite System V (ISAT V)	Space Business Systems/ HS356 (SBS)
Program									
Development Agency	USAF/SSD	USAF/SSD	USAF/SSD	USAF/SSD	NASA	Intelsat	Intelsat	Intelsat	Comsat
Prime Contractor	TRW	GE	TRW	Ford	TRW	Hughes	Hughes	Ford	Hughes
Development Approach	Prototype	Prototype	Prototype	Prototype	Prototype	Prototype	Protoflight	Prototype	Prototype
Development Start	Mar 69	Feb 77	Nov 72	Mar 73	Dec 76	Oct 68	May 73	Sep 76	Dec 77
Launch Vehicle	Titan IIIC	Titan 34D-IUS	Atlas-Centaur	Delta 2914	STS/Atlas-Centaur	Atlas-Centaur	Atlas-Centaur	Atlas/Ariane	Delta 3910/ STS-PAM-D
Primary Mission	Military Strategic	Military Strategic	Military Tactical	Military Strategic	Tracking and Data Relay	Worldwide Commercial	Worldwide Commercial	Worldwide Commercial	Regional Commercial
Spacecraft									
Stabilization Method	Spin	3-Axis	3-Axis	Spin	3-Axis	Spin	Spin	3-Axis	Spin
Dry Weight (lbs)	1,013	1,906	2,090	771	3,403	1,56	1,00	1,945	1,111
BOL Power (watts)	535	1,357	1,574	533	2,400	569	590	1,742	990
EOL Power (watts)	388	975	1,255	375	1,700	460	530	1,290	900
Apogee (nmi)	19,300	19,300	19,300	19,300	19,300	19,300	19,300	19,300	19,300
Perigee (nmi)	19,300	19,300	19,300	19,300	19,300	19,300	19,300	19,300	19,300
Design Life (months)	60	120	60	84	120	84	84	84	120

Note: Dashes denote that data were not available; N/A means "not applicable."

Both protoflight and prototype development approaches are represented among the spacecraft in the database. In the protoflight approach, the first spacecraft built serves not only for qualification testing, but is also the first flight-model spacecraft. In the prototype approach, the first spacecraft built is a dedicated qualification model; the second spacecraft built is the first flight-model. In general, a protoflight development approach is used for one-of-a-kind spacecraft (experimental and scientific missions) and spacecraft that are evolutionary developments of existing spacecraft. The exceptions to this generalization are the planetary spacecraft, where a prototype approach is used for all the programs in our sample.

The 26 programs represent a wide variety in terms of both program and spacecraft attributes. Some attributes and special cases are worth mentioning. In general NASA spacecraft are scientific or experimental in nature and carry a sensor/scientific instrument payload. They usually have short design lives and are developed using a protoflight development approach (excepting the planetary spacecraft) with only one or two units produced. A noteworthy exception is the TDRSS. The TDRSS is an operational communications spacecraft whose development and production were more akin to a typical DoD program. All of our DoD spacecraft were operational spacecraft except for the P-72-2. The P-72-2 was an experimental sensor spacecraft that was part of the Air Force's Space Test Program (STP). It was a one-of-a-kind system whose development more closely resembled NASA programs than the other DoD programs in our database. The SCATHA was a joint STP/NASA program,[1] but we classified it as a NASA program for data presentation purposes.

C. SPACECRAFT DEVELOPMENT PROGRAM SCHEDULES

This subsection summarizes schedule data in tabular form. The data are presented in a manner consistent with the way they are analyzed. We present program schedule data characterizing development through first flight-model delivery and first launch. Sources of the data included the Air Force Space Systems Division (SSD) historical archives, prime contractors, third parties (studies and databases from IDA, NASA, Tecolote, PRC, JPL, etc.), and the open literature. We tried to depend on the primary sources available in the SSD archives or directly from the prime contractors whenever possible. Primary sources

1 The SCATHA's STP designation was P-78-2.

included master schedules and status briefings prepared by the program offices or prime contractors, internal studies of completed programs done by the prime contractors, and data questionnaires prepared by IDA and completed by the prime contractors. Wherever possible we corroborated milestone dates using multiple sources.

Tables III-4, III-5, and III-6 present major milestones for eight DoD sensor/navigation spacecraft programs, nine NASA scientific/experimental programs, and nine operational communications spacecraft programs. Only a few of the spacecraft programs were subject to the classic DoD systems acquisition approach. For most of the programs, the first flight-model spacecraft, which was always used as an operational system, was procured under the original development contract. In other programs, the development contract only covered the qualification model spacecraft with the first flight-model being bought under the first production contract. For programs with a protoflight development approach, the qualification model and first flight-model were the same.

In order to compare across programs, milestone dates were normalized to a common milestone, development start. We defined development start as the authority to proceed (ATP) for engineering development. For DoD spacecraft, ATP generally corresponds to the start of the full-scale development (FSD) contract. For NASA spacecraft, the equivalent would be the start of the phase C/D contract. Development start was used because it represents the most unambiguous base point common to all programs; normalized milestones are expressed as months from development start. Four schedule intervals are included in the summary tables: preliminary design review (PDR), critical design review (CDR), first flight-model delivery, and first launch.

In some cases, the delivery date of the first flight-article is ambiguous. When a delivery date was not specified, we often used either the acceptance test completion date (e.g. DSCS III) or the date when the spacecraft was ready for shipping to the launch site (e.g. NATO III, FLTSAT, where in the case of FLTSAT formal delivery was taken at the launch site prior to launch). Where we have complete information on a program, the alternative milestone dates are either the same as delivery or fall within a month or two. Included in Appendix B are more detailed bibliographic information and explanations of the schedule data for each program.

Table III-4. Program Milestones and Intervals for DoD Sensor/Navigation Spacecraft Programs

	Sensor Spacecraft						Navigation Spacecraft	
	DMSP 5D-1	DMSP 5D-2	DSP 1	DSP 5R	DSP 14	P72-2	GPS I	GPS II
Calendar Dates								
Development Start	Mar 72	Apr 75	Dec 66	Oct 78	Nov 81	Jul 72	Jun 74	Dec 80
PDR	Jul 72	May 75	Nov 67	Mar 79	May 82	Oct 72	Feb 75	Aug 81
CDR	Mar 73	Nov 75	Dec 68	—	May 83	Apr 73	Jun 75	Mar 82
First Delivery	Jun 76	Mar 82	Oct 70	Nov 84	Dec 88	Mar 75	Jan 78	Apr 87
First Launch	Sep 76	Dec 82	Classified	Classified	Classified	Apr 75	Feb 78	Feb 89
Months from Dev. Start								
PDR	4	1	12	5	6	3	8	8
CDR	12	7	24	—	18	9	12	15
First Delivery	51	83	46	73	86	32	43	76
First Launch	54	92	Classified	Classified	Classified	33	44	98

Note: Dashes denote that data were not available.

Table III-5. Program Milestones and Intervals for NASA Scientific/Experimental Spacecraft Programs

	Earth Orbiting					Planetary			
	AEM-HCMM	AE-C	HEAO	HST	SCATHA	Mariner 5	Mariner 6	Mariner 10	Viking Orbiter
Calendar Dates									
Development Start	Dec 74	Oct 71	May 72	Oct 77	Mar 76	Dec 65	Feb 66	Apr 71	Feb 70
PDR	—	Feb 72	May 75	May 79	Jan 77	—	Mar 67	—	Oct 71
CDR	—	Aug 72	Feb 76	Mar 82	May 77	Apr 66	Nov 67	—	Jul 73
First Delivery	Aug 77	Dec 73	Apr 77	Jul 86	Oct 78	Apr 67	Dec 68	Aug 73	Feb 75
First Launch	Apr 78	Dec 73	Aug 77	Apr 90	Feb 79	Jun 67	Feb 69	Nov 73	Aug 75
Months from Dev. Start									
PDR	—	4	35	19	10	—	13	—	20
CDR	—	10	45	53	14	4	21	—	41
First Delivery	32	26	59	105	31	16	34	28	60
	40	26	63	150	35	18	36	31	66

Note: Dashes denote that data were not available.

Table III-6. Program Milestones and Intervals for Operational Communications Spacecraft Programs

	DoD/NASA					Commercial			
	DSCS II	DSCS III	FLTSAT	NATO III	TDRSS	ISAT IV	ISAT IVA	ISAT V	SBS
Calendar Dates									
Development Start	Mar 69	Feb 77	Nov 72	Mar 73	Dec 76	Oct 68	May 73	Sep 76	Dec 77
PDR	Jul 69	Nov 76	Jul 73	—	Apr 77	—	Dec 73	—	Apr 78
CDR	Sep 70	May 78	Dec 74	—	Aug 78	—	Jul 74	—	Jan 79
First Delivery	Sep 71	Jun 81	Dec 77	Mar 76	Dec 82	Dec 70	Aug 75	Oct 80	Sep 80
First Launch	Nov 71	Oct 82	Feb 78	Apr 76	Apr 83	Jan 71	Sep 75	Dec 80	Nov 80
Months from Dev. Start									
PDR	4	-3	8	—	4	—	7	—	4
CDR	18	15	25	—	20	—	14	—	13
First Delivery	30	52	61	36	72	26	27	49	33
First Launch	32	68	63	37	76	27	28	51	35

Note: Dashes denote that data were not available.

D. SPACECRAFT MANUFACTURING SCHEDULES

We collected data on manufacturing milestones of flight-model spacecraft for programs that entered series production. We were able to locate data for nine production programs. Almost all of the data came from primary sources associated with the program offices and prime contractors. Data on manufacturing schedules were perhaps the most difficult to collect and interpret. Each contractor, and even each program, reported data in a different format with different availability for each milestone. Although the relationships in the data are almost always logically consistent (i.e. fabrication start before assembly start, assembly start before system test start) there are some ambiguities. For example, most programs show assembly completion occurring after system test start. Often integration tests are started on the spacecraft bus before the final mating of the payload and bus. Even after trying to collect and interpret the data consistently, we found inconsistencies in milestone definitions across programs. However, we believe that on average the data provides useful insights into spacecraft production schedules.

Tables III-7 and III-8 present manufacturing milestones for DoD sensor/navigation and operational communications spacecraft. Each column represents a production run of a given spacecraft. The range of numbers below each column heading corresponds to the numbering of the spacecraft in terms of the total production for that family of spacecraft (e.g. the first GPS-II flight-model spacecraft was the 13th spacecraft within the GPS family). Usually each production run corresponds to a physically different spacecraft, which is treated as a unique system in the rest of the database. The two exceptions are the DMSP 5D-2 (11-14) and the DSCS III (8-14), which are continuations of previous spacecraft designs. In some instances, such as the GPS II, we truncated the data for a production run due to large changes in the program. GPS II delivery schedules were extended in midstream because of the unavailability of launch resources. In all, we have manufacturing data on nine different spacecraft designs. Also included in the tables are summary data for each manufacturing program.

In normalizing the manufacturing data to a common milestone, we chose a different approach than was used for the development data. For the manufacturing data, the most widely available and consistently defined milestone is the end of acceptance testing. When determining normalized intervals we calculated backwards from this milestone to the other manufacturing milestones for which data were available. Manufacturing intervals are presented in Tables III-9 and III-10.

Table III-7. Manufacturing Schedules for DoD Sensor/Navigation Spacecraft

Production Milestones	DMSP 5D-1 (1–5)	DMSP 5D-2 (5–10)	DMSP 5D-2 (11–14)	DSP 1 (1–4)	DSP 14 (14–17)	GPS II (13–19)
Spacecraft 1						
Start Fabrication	—	—	—	—	Oct 82	—
Start System Assembly	—	—	—	—	Apr 85	Sep 84
Complete System Assembly	—	—	—	—	Jul 87	Jan 86
Start System Testing	Jun 74	Jul 79	—	Dec 69	May 87	Jan 86
Complete Acceptance Testing	Jun 76	Jan 82	—	Sep 70	Aug 88	Apr 87
Spacecraft 2						
Start Fabrication	—	—	—	—	Sep 83	—
Start System Assembly	—	—	—	—	Mar 86	—
Complete System Assembly	—	—	—	—	Apr 87	Oct 86
Start System Testing	Jan 76	Nov 80	Mar 86	Feb 70	Apr 87	Nov 86
Complete Acceptance Testing	Mar 77	Jun 83	Dec 88	Feb 71	Jun 90	Jul 87
Spacecraft 3						
Start Fabrication	—	—	—	—	—	—
Start System Assembly	—	—	—	—	May 88	—
Complete System Assembly	—	—	—	—	Sep 89	Dec 86
Start System Testing	Nov 76	Mar 82	Feb 87	Jul 70	Sep 89	Feb 87
Complete Acceptance Testing	Oct 77	Mar 84	Oct 89	Apr 71	Aug 91	Dec 87
Spacecraft 4						
Start Fabrication	—	—	—	—	—	—
Start System Assembly	—	—	—	—	Jun 88	—
Complete System Assembly	—	—	—	—	Aug 90	May 87
Start System Testing	—	Sep 84	Feb 88	Dec 70		May 87
Complete Acceptance Testing	Feb 78	Jan 87	Aug 90	Jun 71		Apr 88
Spacecraft 5						
Start Fabrication	—	—				—
Start System Assembly	—	—				—
Complete System Assembly	—	—				Jul 87
Start System Testing	—	Mar 84				Jul 87
Complete Acceptance Testing	May 78	Oct 87				Aug 89
Spacecraft 6						
Start Fabrication						—
Start System Assembly						—
Complete System Assembly						Sep 87
Start System Testing						Sep 87
Complete Acceptance Testing						Jul 88
Summary Data						
Number of Spacecraft Delivered	5	9		4	3	6
Average Delivery Rate Per Year	2.09	0.93		4.01	0.67	2.14
Average Months Between Deliveries	5.7	12.9		3.0	18.0	5.6

Note: Dashes denote that data were not available.

Table III-8. Manufacturing Schedules for Communications Spacecraft

Production Milestones	FLTSAT (1–5)	TDRSS (1–5)	DSCS III (1–8)	DSCS III (8–14)	NATO III (A–C)
Spacecraft 1					
Start Fabrication	Sep 75	Oct 77	Sep 78	Mar 85	—
Start System Assembly	Dec 76	—	—	May 86	Apr 75
Complete System Assembly	May 77	—	—	Jun 87	Sep 75
Start System Testing	Aug 76	Jun 79	Jul 80	Jun 87	Sep 75
Complete Acceptance Testing	Dec 77	Nov 82	May 81	Feb 88	Feb 76
Spacecraft 2					
Start Fabrication	Apr 76	—	Jan 79	Feb 86	—
Start System Assembly	Jan 77	—	Apr 80	Sep 86	—
Complete System Assembly	Nov 77	—	Jul 81	Aug 87	Jun 76
Start System Testing	Jan 77	Jan 80	Jul 81	Aug 87	Jun 76
Complete Acceptance Testing	Mar 79	Nov 84	Jul 82	May 88	Dec 76
Spacecraft 3					
Start Fabrication	Dec 76	—	Feb 84	May 86	—
Start System Assembly	Dec 77	—	Nov 84	Feb 87	Dec 77
Complete System Assembly	Dec 78	—	Dec 85	Jan 88	Apr 78
Start System Testing	Dec 77	Dec 82	Dec 85	Jan 88	Apr 78
Complete Acceptance Testing	Oct-79	Jan 85	Jan 87	Dec 88	Sep 78
Spacecraft 4					
Start Fabrication	Oct 78	—			
Start System Assembly	Dec 79	—	May 83	Jul 87	
Complete System Assembly	Feb 80	—	May 84	Jun 88	
Start System Testing	Sep 79	Jun 83	May 84	Jun 88	
Complete Acceptance Testing	Sep 80	Dec 85	Nov 84	Apr 89	
Spacecraft 5					
Start Fabrication	Nov 78	—	—	—	
Start System Assembly	—	—	Sep 83	Dec 87	
Complete System Assembly	—	—	Aug 84	Jan 89	
Start System Testing	Feb 80	Jun 83	Aug 84	Jan 89	
Complete Acceptance Testing	Jun 81	Jun 85	Jun 85	Oct 89	
Spacecraft 6					
Start Fabrication		—	Jan 84	—	
Start System Assembly		—	Jun 84	May 88	
Complete System Assembly		—	—	Jun 89	
Start System Testing		Jan 84	Aug 85	Jun 89	
Complete Acceptance Testing		Jan 86	Nov 86	Dec 89	
Spacecraft 7					
Start Fabrication			Jan 84		
Start System Assembly			Aug 85	Oct 88	
Complete System Assembly			Feb 87	Jun 90	
Start System Testing			Feb 87	Jun 90	
Complete Acceptance Testing			Sep 87	Sep 90	
Summary Information					
Number of Spacecraft Delivered	5	5	14		3
Average Delivery Rate Per Year	1.14	1.55	1.39		0.77
Average Months Between Deliveries	10.5	7.8	8.6		15.5

Note: Dashes denote that data were not available.

Table III-9. Manufacturing Milestone Intervals for DoD Sensor/Navigation Spacecraft

	Months from Acceptance Test Completion					
	DMSP 5D-1	DMSP 5D-2		DSP	DSP	GPS II
Production Milestones	(1–5)	(6–10)	(11–14)	(1–4)	(14–17)	(13-19)
Spacecraft 1						
Start Fabrication	—	—	—	—	70	—
Start System Assembly	—	—	—	—	40	31
Complete System Assembly	—	—	—	—	13	15
Start System Testing	24	30	—	9	15	15
Spacecraft 2						
Start Fabrication	—	—	—	—	81	—
Start System Assembly	—	—	—	—	51	—
Complete System Assembly	—	—	—	—	38	9
Start System Testing	14	31	33	12	38	8
Spacecraft 3						
Start Fabrication	—	—	—	—	—	—
Start System Assembly	—	—	—	—	39	—
Complete System Assembly	—	—	—	—	23	12
Start System Testing	11	24	32	9	23	10
Spacecraft 4						
Start Fabrication		—	—	—	—	—
Start System Assembly		—	—	—	—	—
Complete System Assembly		—	—	—	—	11
Start System Testing		28	30	6	—	11
Spacecraft 5						
Start Fabrication		—				—
Start System Assembly		—				—
Complete System Assembly		—				25
Start System Testing		43				25
Spacecraft 6						
Start Fabrication						—
Start System Assembly						—
Complete System Assembly						10
Start System Testing						10

Note: Dashes denote that data were not available.

Table III-10. Manufacturing Milestone Intervals for Communications Spacecraft

	Months from Acceptance Test Completion				
	FLTSAT	TDRSS	DSCS III	DSCS III	NATO III
Production Milestones	(1–5)	(1–5)	(1–8)	(8–14)	(A–C)
Spacecraft 1					
Start Fabrication	27	61	32	35	—
Start System Assembly	12	—	—	21	10
Complete System Assembly	7	—	—	8	5
Start System Testing	16	41	10	8	5
Spacecraft 2					
Start Fabrication	35	—	42	27	—
Start System Assembly	26	—	27	20	—
Complete System Assembly	16	—	12	9	6
Start System Testing	26	58	12	9	6
Spacecraft 3					
Start Fabrication	34	—	35	31	—
Start System Assembly	22	—	26	22	9
Complete System Assembly	10	—	13	11	5
Start System Testing	22	25	13	11	5
Spacecraft 4					
Start Fabrication	23	—	—	—	
Start System Assembly	9	—	18	21	
Complete System Assembly	7	—	6	10	
Start System Testing	12	30	6	10	
Spacecraft 5					
Start Fabrication	31	—	—	—	
Start System Assembly	—	—	21	22	
Complete System Assembly	—	—	10	9	
Start System Testing	16	24	10	9	
Spacecraft 6					
Start Fabrication		—	34	—	
Start System Assembly		—	29	19	
Complete System Assembly		—	—	6	
Start System Testing		24	15	6	
Spacecraft 7					
Start Fabrication			44	—	
Start System Assembly			25	23	
Complete System Assembly			7	3	
Start System Testing			7	3	

Note: Dashes denote that data were not available.

E. SOFTWARE CHARACTERISTICS AND SCHEDULES

We collected data at the CSCI level for a wide variety of software projects. Primary sources of software data included the NASA/JPL database [12] and the Space System Cost Analysis Group (SSCAG) database [13]. Both databases were normalized and analyzed separately and in combination. The NASA database consists mostly of space-system software based both on the ground and in space. The 1991 version of the SSCAG database is by far the largest and contains a wide variety of software programs designed to operate in many different types of systems and environments. Unfortunately, the schedule and other data could not be normalized properly due to a lack of information.[2] After analyzing the data in several different ways, we judged the NASA data to be the most appropriate for the purpose of our analysis.

The data were classified by two different categorization schemes, environment and type. The environment is where the software is physically deployed and executed. Two environments are represented in our analyses:

- Space—software on an orbiting vehicle and sub-orbital probes, the most expensive per line of code for a given type.
- Ground—software on the ground, the least expensive per line of code for a given type.

Software types are grouped into three categories: system, application, and support:

- System—software developed for a specific computer system or family of computer systems to facilitate the operation and maintenance of the computer system and associated programs (e.g. operating system, executive). It is the most expensive per line of code within an environment.
- Application—software developed for the functional use of a computer system (e.g. target tracking, navigation, weapon assignment, mission management).
- Support—off-line software (e.g. simulation/training, maintenance, report generator, site support, delivered test software). It is the least expensive per line of code within an environment.

The categorization of application, system, and support software was not always exact; we used our best judgment for marginal cases.

Other variables of interest include thousands of source lines of code (KSLOC), and average staff size (headcount). Software development duration is defined as months from preliminary design start to CSCI integration and test.

Table III-11 presents both schedule and programmatic data for 51 CSCI developments.

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2 As part of a follow-on IDA task, the SSCAG database is to be normalized using recently obtained information.

Table III-11. Software Data

Program Type	KSLOC	Average Staff Size	Software Type	Environment	Development Duration (Months)
Earth-Orbiting Sensor	29.5	5.2	Support	Ground	23
Earth-Orbiting Sensor	19.7	1.6	Application	Ground	37.1
Earth-Orbiting Sensor	66.6	8.1	Application	Ground	37.1
Earth-Orbiting Sensor	5.5	3	Application	Ground	6.1
Earth-Orbiting Sensor	10.4	7.5	Application	Ground	6.6
Earth-Orbiting Sensor	14	9	Application	Ground	6.6
Earth-Orbiting Sensor	16	7.5	Application	Ground	15.3
Earth-Orbiting Sensor	6.5	2.7	Application	Ground	15.3
Earth-Orbiting Sensor	13	3.9	Application	Ground	15.3
Earth-Orbiting Sensor	8	2.7	Application	Ground	15.3
Earth-Orbiting Sensor	24	7.8	Support	Ground	15.3
Earth-Orbiting Sensor	90	29	Application	Ground	15.3
Earth-Orbiting Sensor	48.5	7.9	Support	Ground	30.1
Earth-Orbiting Sensor	32.6	5.6	Support	Ground	30.1
Earth-Orbiting Sensor	12.8	2.1	Application	Ground	30.1
Earth-Orbiting Sensor	15.4	2.3	Support	Ground	30.1
Earth-Orbiting Sensor	16.3	2.7	Support	Ground	30.1
Earth-Orbiting Sensor	35.5	6.4	Support	Ground	30.1
Earth-Orbiting Sensor	16.5	12	Application	Space	44.1
Earth-Orbiting Sensor	13.3	10.9	Application	Space	44.1
Earth-Orbiting Sensor	1.7	0.3	System	Space	44.1
Earth-Orbiting Sensor	1.5	0.9	Application	Space	44.1
Earth-Orbiting Sensor	177.9	26.5	Application	Ground	47.1
Earth-Orbiting Sensor	25.9	6.3	Application	Ground	18.7
Earth-Orbiting Sensor	24.6	6.3	Application	Ground	18.7
Earth-Orbiting Sensor	66.6	15.9	Application	Ground	22.2
Manned Space	40	5	System	Ground	30
Manned Space	90	1.1	System	Ground	143.2
Manned Space	240	6.2	System	Ground	31.1
Manned Space	66	5	System	Ground	60
Manned Space	98	3.3	System	Ground	23
Manned Space	150	12.2	System	Ground	72.1
Manned Space	137	12.2	System	Ground	52
Manned Space	79	21.1	System	Ground	19
Manned Space	339	8.4	System	Ground	53.1
Manned Space	70	3.7	Application	Ground	75.1
Manned Space	227	25.1	Application	Ground	47.1
Manned Space	41	16.9	System	Space	35.5
Planetary	150	2.8	Application	Ground	117.1
Planetary	100	5	Application	Ground	72.1
Planetary	100	2.2	Application	Ground	96.1
Planetary	100	3.7	Support	Ground	96.1
Planetary	.15	2	Application	Ground	24
Planetary	75	1.7	Application	Ground	36.1
Planetary	32.5	1.7	Application	Ground	36.1
Planetary	31.5	2.5	Application	Ground	24
Planetary	6.3	0.5	Application	Ground	48.3
Planetary	11.3	1.5	Support	Ground	24
Planetary	20	0.7	Application	Ground	96.1
Planetary	20	1	Application	Ground	48.1
Planetary	3	0.5	Application	Ground	48.1

IV. DATA ANALYSIS

Analyses of the data presented in the previous chapter were separated into three parts. The major portion of the analyses dealt with the spacecraft engineering development schedules. We separately analyzed spacecraft manufacturing milestone intervals through acceptance testing. Software development schedules, although related to the overall development schedule, were also treated separately.

A. APPROACH

We used linear regression analysis to define and test time-estimating relationships (TERs). In regression analyses schedule intervals measured in months were treated as dependent variables and regressed against independent variables which we hypothesized to be schedule drivers. Candidate schedule drivers included spacecraft technical and program variables that characterize size and complexity of program efforts and thus might be correlated to schedule length.

The resulting TERs took on the intrinsically linear multiplicative form $Y = ax^b$. In estimating the coefficients of this equation form, we first transformed the equation to a log-log form and then applied standard linear regression techniques. The classical normal regression assumption is that the residuals are additive and are normally distributed in log-log space with an expected value and mode of zero. When the equation is transformed from the log-log form back to a multiplicative form, the assumption implies that the resulting residuals are multiplicative and distributed log normally with a mode of one. Because the log-normal distribution is right-skewed, the expected value and mode of the residuals are no longer equal. The unadjusted multiplicative equation would yield values of the dependent variable that correspond to the mode.

An adjustment must had to be made for the multiplicative form to yield the expected value of the dependent variable. This adjustment was made to our TERs by adding one-half of the regression mean square error to the intercept term of the log-log equation before its transformation into the multiplicative form. After the intercept term was transformed into a multiplicative constant, we calculated an adjustment factor (adjusted constant term/unadjusted constant term) where the adjustment factor is always greater than one. In reporting the estimating relationships, we report the adjusted multiplicative equation along with the factor, so the equation can be back-adjusted to yield the mode (most-likely value).

Other information describing the estimating relationships include the number of data observations used in the regression (N), R^2, adjusted R^2, the standard error of the estimate (SEE) and levels of statistical significance for each of the parameter estimates. R^2 measures the proportion of the total variance in the data explained by the model; adjusted R^2 presents this information adjusted for the number of independent variables in the regression. R^2 and adjusted R^2 are calculated from the data and model after they are transformed back from log space to arithmetic space. The SEE is calculated in log space; it can be converted into minus/plus percentages of the Y values in arithmetic space by the relationships: $(e^{-SEE}) - 1$ and $(e^{+SEE}) - 1$. The level of statistical significance for a parameter estimate describes the probability that we are incorrect when we reject the null hypothesis that b = 0 (i.e. that the independent variable of interest has no effect on schedule length).[3] Our rule of thumb is to exclude variables whose parameter estimates are not significant at the .1 level . When we report probability levels, values that are less than .01 are rounded to .01.

B. DEVELOPMENT SCHEDULES

For the purpose of our analyses, we define the development program schedule as beginning with the authority to proceed (ATP) for engineering development and ending with the delivery of the first flight-model spacecraft. Milestone definitions are included in Chapter III.

In analyzing the schedule interval data, we found the most satisfactory estimating relationships for overall program length. We also tested relationships for intervals at more disaggregated levels such as time from development start to CDR and time from CDR to first production delivery. These relationships proved less satisfactory than the models estimated at the more aggregated level. We report a single estimating relationship for each of the disaggregated intervals.

1. Data Sample Description

The data on the 26 unmanned spacecraft described in Chapter III were used for this analysis.

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[3] For the parameter estimates on 1/0 dummy variables, which have been transformed to yield multiplicative factors, the null hypothesis is that b = 1.

The candidate schedule drivers tested were:

- Beginning of life power in watts (BOL Power).
- End of life power in watts (EOL Power).
- Spacecraft dry weight in pounds (SCWT).
- Design life in months (DESLIF).
- Sensor dummy variable (SENSOR). A dummy variable with a value of 1 for spacecraft whose primary payload is a sensor or scientific instrument package and a value of 0 otherwise.
- Navigation dummy variable (NAV). A dummy variable with a value of 1 for spacecraft whose primary mission is navigation and a value of 0 otherwise.
- Commercial spacecraft dummy variable (COMMER). A dummy variable with a value of 1 for spacecraft developed for a commercial user and a value of 0 otherwise.
- Protoflight dummy variable (PROTOFLY). A dummy variable with a value of 1 for spacecraft developed using a protoflight development approach and a value of 0 for spacecraft using a prototype development approach.
- NASA Earth-orbiting experimental/scientific spacecraft dummy variable (NASA E.O.). A dummy variable with a value of 1 for NASA scientific spacecraft that perform their missions from Earth orbit and a value of 0 otherwise. Note that NASA's TDRSS, which is an operational communications spacecraft, does not fit into this category.
- Experimental/scientific Earth-orbiting spacecraft dummy variable (EXPR). The values of this variable are identical to those for the NASA E.O. variable, except the Air Force's P-72-2 is classified as an experimental/scientific spacecraft.
- Planetary scientific spacecraft dummy variable (PLANET). A dummy variable with a value of 1 for scientific spacecraft that perform their missions beyond Earth orbit and a value of 0 otherwise.

Given the number of data points available, we where able to stratify the database into more homogeneous data categories for analysis. In addition to the full 26-observation (N = 26) data set the categories include:

- Earth-orbiting spacecraft (N = 21). The total database less the planetary exploration spacecraft and the Hubble Space Telescope.
- Operational spacecraft (N = 16). Spacecraft in the database with an operational mission as opposed to a experimental/scientific mission. The spacecraft include communications, navigation and sensor spacecraft. Operational spacecraft are distinguished by the fact that they are built in series production. All DoD

spacecraft are operational with the exception of the P-72-2, an experimental spacecraft.

- Earth-orbiting sensor spacecraft (N = 11). Earth-orbiting spacecraft whose primary payload is a sensor or scientific instrument package. Included are both operational and experimental/scientific spacecraft.

- Operational communications spacecraft (N = 9). Spacecraft whose primary mission is communications.

2. Time-Estimating Relationships

a. Full Data Sample

In developing a regression model to estimate the number of months required from development start to the delivery of the first production spacecraft (1stDEL), many different specifications were tested. Measures of spacecraft size and complexity proved to be good explanatory variables. The most satisfying of these measures is BOL power. Other variables that were statistically significant were all 1/0 dummy variables. The dummy variables include those for sensor, navigation, planetary, and commercial spacecraft. The resulting estimating relationship and measures of statistical significance and model fit are presented below in equation 1.0.

$$1stDEL = 1.394\,(BOL\ Power)^{.508}\ \underset{(.01)(.01)}{1.351^{(SENSOR)}}\ \underset{(.01)}{1.476^{(NAV)}}\ \underset{(.03)}{.762^{(COMMER)}}\ \underset{(.01)}{.596^{(PLANET)}} \qquad [1.0]$$

N = 26 R^2 = .87 Adjusted R^2 = .84 SEE = .168 Intercept adjustment = 1.014

Significance levels are in parentheses below the parameter estimates. When the equation is divided by the intercept adjustment factor, it will then yield most-likely values. The regression results show all parameter estimates significant at the .03 level or better.

The "baseline" case (i.e. where all the dummy variables equal zero) is relevant to communications spacecraft developed for a government user. For the most part, the parameter estimates are consistent with intuition. The positive coefficient on BOL Power was consistent with our expectations. BOL Power is a proxy for spacecraft mission performance, size, and complexity, including the performance and complexity of the payload. Also the spacecraft's electrical power system (EPS) is often a critical path item. We found BOL Power to provide a considerably better fit than dry weight, another candidate schedule driver that was included in two of the previous studies reviewed in Chapter II.

Intuition tells us that, for a given level of power, sensor spacecraft should be more difficult to develop than communications spacecraft; the parameter estimate for the sensor variable indicates a multiple of 1.351 for time to first delivery. Likewise, navigation spacecraft would also be expected to be more difficult to develop than communications spacecraft; the estimated multiple is 1.48. We did not expect navigation spacecraft to take longer to develop than sensor spacecraft. However, because our sample included only two navigation spacecraft, that result should be applied cautiously.

We did expect commercial spacecraft to take a shorter time to develop than government procured spacecraft. The estimated coefficient of .762 may be due to a variety of reasons: commercial procurement practices can be less burdensome than DoD or NASA practices, commercial spacecraft tend to be less technologically ambitious, and they do not have to meet unique military requirements such as nuclear-hardening.

The least expected result was the coefficient of .596 on the planetary spacecraft dummy variable. There is no a priori reason to believe that planetary spacecraft should take a shorter time to develop than Earth-orbiting spacecraft, once power is taken into account. One explanation for the result is that our sample of planetary spacecraft is not typical; three of the four planetary programs started in the mid- to late 1960s and were a part of the Mariner family of spacecraft. The Mariner series enjoyed a great deal of design inheritance from mission to mission. The newest planetary spacecraft, the Viking Orbiter, is greatly underestimated by equation 1.0. Also, as BOL Power is estimated at Earth, and not at the spacecraft's destination, the amount of power required to drive the spacecraft's systems and mission equipment is considerably less than the BOL Power. Thus, a given amount of complexity would tend to be associated with a higher level of power for planetary spacecraft. Caution should be used in estimating future planetary missions using equation 1.0.

We expected that protoflight programs would take a shorter time than prototype programs because in protoflight programs the first full-up test article built is the first flown. However, the PROTOFLY dummy variable was not statistically significant. The DoD modification programs, most of which used the protoflight approach, entailed relatively lengthy developments.

Figure IV-1 shows first delivery times predicted by equation 1.0 plotted against actual program delivery times. Table IV-1 summarizes the prediction errors associated with how well the model fits the data in arithmetic space. Also included are the multiplicative residuals, which are a better indicator of how each data point fits the model in the log-log space in which it was estimated. For example, although the HST is by far the largest outlier in terms of absolute error in arithmetic space (22.1 months), its multiplicative residual is unremarkable.

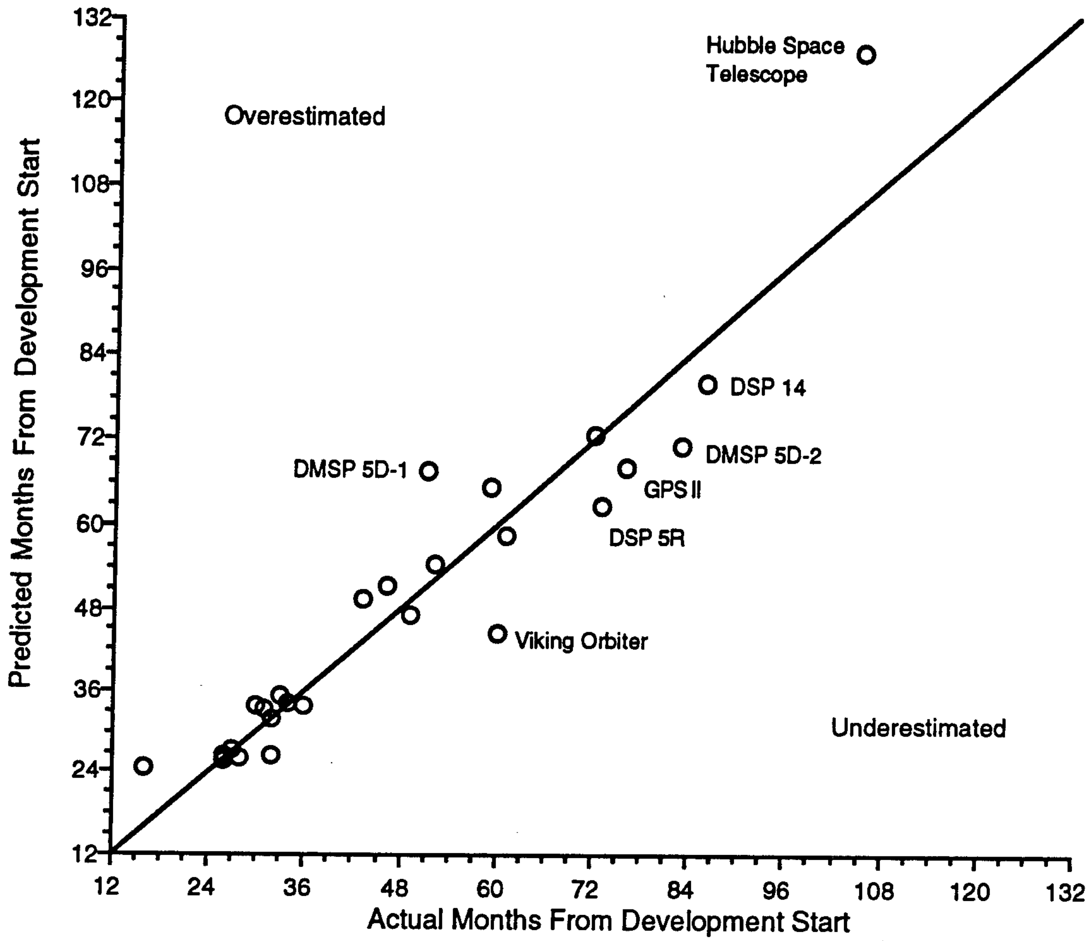


Figure IV-1. Equation 1.0 Predicted Versus Actual Months From Development Start to First Delivery

Notable data points include the Viking Orbiter and Hubble Space Telescope (HST). The Viking, which is greatly underestimated, may be more typical of contemporary planetary spacecraft in terms of schedule when compared to the Mariner series. The HST is by far the largest and highest-powered spacecraft in the data sample and is overestimated by the model by over two years. The Gamma Ray Observatory (GRO), a spacecraft of similar size and power for which some preliminary data were available, would be overestimated by an even greater amount.

Table IV-1. Equation 1.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
AEM-HCMM	32	26.3	5.7	1.22
AE-C	26	25.6	0.4	1.02
DMSP 5D-1	51	67.6	-16.6	0.75
DMSP 5D-2	83	70.9	12.1	1.17
DSCS II	30	33.9	-3.9	0.89
DSCS III	52	54.3	-2.3	0.96
DSP 1	46	51.3	-5.3	0.90
DSP 14	86	79.8	6.2	1.08
DSP 5R	73	62.5	10.5	1.17
FLTSAT	61	58.6	2.4	1.04
GPS I	43	49.4	-6.4	0.87
GPS II	76	68.0	8.0	1.12
HEAO	59	65.5	-6.5	0.90
HST	105	127.1	-22.1	0.83
ISAT IV	26	26.6	-0.6	0.98
ISAT IVA	27	27.1	-0.1	0.99
ISAT V	49	47.0	2.0	1.04
Mariner 5	16	24.4	-8.4	0.66
Mariner 6	34	34.1	-0.1	1.00
Mariner 10	28	26.1	1.9	1.07
NATO III	36	33.8	2.2	1.06
P-72-2	32	31.7	0.3	1.01
SBS	33	35.3	-2.3	0.93
SCATHA	31	33.5	-2.5	0.92
TDRSS	72	72.6	-0.6	0.99
Viking Orbiter	60	44.5	15.5	1.35

Although the HST is not an overly influential data point according to the regression diagnostics, the pattern of residuals evident when the HST is included in the database is not very pleasing. Four of the five spacecraft with actual values for the dependent variable greater than 72 months (excluding the HST) are underestimated by the model. Given this and the fact that the model does poorly with very high-powered spacecraft, we decided to estimate an alternative model without the HST. The resulting estimating relationship and measures of statistical significance and model fit are presented in equation 1.1.

$$\text{1stDEL} = 1.110\ (\text{BOL Power})^{\underset{(.01)}{.540}}\ \underset{(.01)}{1.403}^{(\text{SENSOR})}\ \underset{(.01)}{1.496}^{(\text{NAV})}\ \underset{(.03)}{.768}^{(\text{COMMER})}\ \underset{(.01)}{.582}^{(\text{PLANET})} \qquad [1.1]$$

N = 25 $\quad R^2 = .89 \quad$ Adjusted $R^2 = .85 \quad$ SEE = .166 $\quad$ Intercept adjustment = 1.014

Parameter estimates are little changed from those of equation 1.0. The parameter estimate most changed is that for BOL Power, which rises from .508 to .540. Equation 1.1

should be used with the proviso that the spacecraft being estimated should not have a BOL power greatly exceeding the 2,400-watt maximum evident in the database.

Figure IV-2 shows first delivery times predicted by equation 1.1 plotted against program actuals. Table IV-2 summarizes the prediction errors associated with fitting the equation to the data.

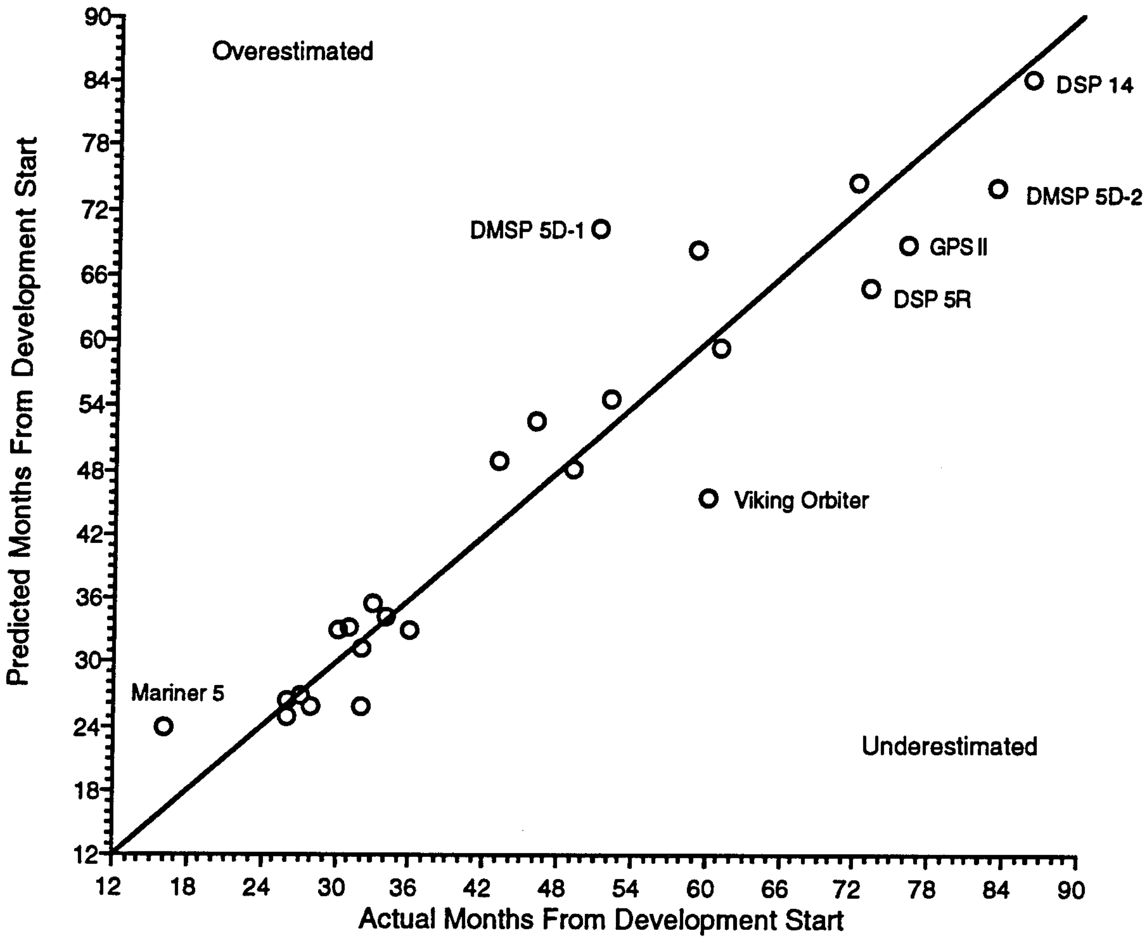


Figure IV-2. Equation 1.1 Predicted Versus Actual Months From Development Start to First Delivery

The residuals show more of a random scatter when the HST is dropped from the data set. Notable data points include the Viking Orbiter (again) and the DMSP 5D-1. The DMSP 5D-1 was an evolutionary development on an earlier DMSP design, and a minimum of difficulty was encountered in the course of the development program. This contrasts with the other DoD spacecraft that were modifications of existing systems. Considerable schedule delays, some of which were caused by changes in requirements, occurred in the

DSP 5R/6R, DSP 14, DMSP 5D-2, and GPS II programs. All of these programs are underestimated by equation 1.1.

Table IV-2. Equation 1.1 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
AEM-HCMM	32	25.8	6.2	1.24
AE-C	26	25.0	1.0	1.04
DMSP 5D-1	51	70.3	-19.3	0.73
DMSP 5D-2	83	74.0	9.0	1.12
DSCS II	30	33.1	-3.1	0.91
DSCS III	52	54.7	-2.7	0.95
DSP 1	46	52.5	-6.5	0.88
DSP 14	86	84.0	2.0	1.02
DSP 5R	73	64.8	8.2	1.13
FLTSAT	61	59.3	1.7	1.03
GPS I	43	48.9	-5.9	0.88
GPS II	76	68.7	7.3	1.11
HEAO	59	68.1	-9.1	0.87
ISAT IV	26	26.3	-0.3	0.99
ISAT IVA	27	26.8	0.2	1.01
ISAT V	49	48.1	0.9	1.02
Mariner 5	16	24.0	-8.0	0.67
Mariner 6	34	34.3	-0.3	0.99
Mariner 10	28	25.8	2.2	1.09
NATO III	36	33.0	3.0	1.09
P-72-2	32	31.4	0.6	1.02
SBS	33	35.4	-2.4	0.93
SCATHA	31	33.4	-2.4	0.93
TDRSS	72	74.5	-2.5	0.97
Viking Orbiter	60	45.5	14.5	1.32

b. Earth-Orbiting Spacecraft

We created a more homogenous database by excluding the planetary spacecraft from the database used to estimate equation 1.1. We also excluded the HST because of the lessons learned from our experience with the full data set. The first equation estimated from the new database uses the same specification as equations 1.0 and 1.1. The resulting estimating relationship and measures of statistical significance and model fit are presented in equation 2.0.

$$\text{1stDEL} = 1.431\ (\text{BOL Power})^{.503}\ 1.371^{(\text{SENSOR})}\ 1.473^{(\text{NAV})}\ .762^{(\text{COMMER})} \qquad [2.0]$$

(.01) (.01) (.01) (.01)

N = 21 R^2 = .90 Adjusted R^2 = .87 SEE = .127 Intercept adjustment = 1.008

Figure IV-3 shows the values predicted by equation 2.0 plotted against program actuals. Table IV-3 summarizes the prediction errors associated with fitting the equation to the data.

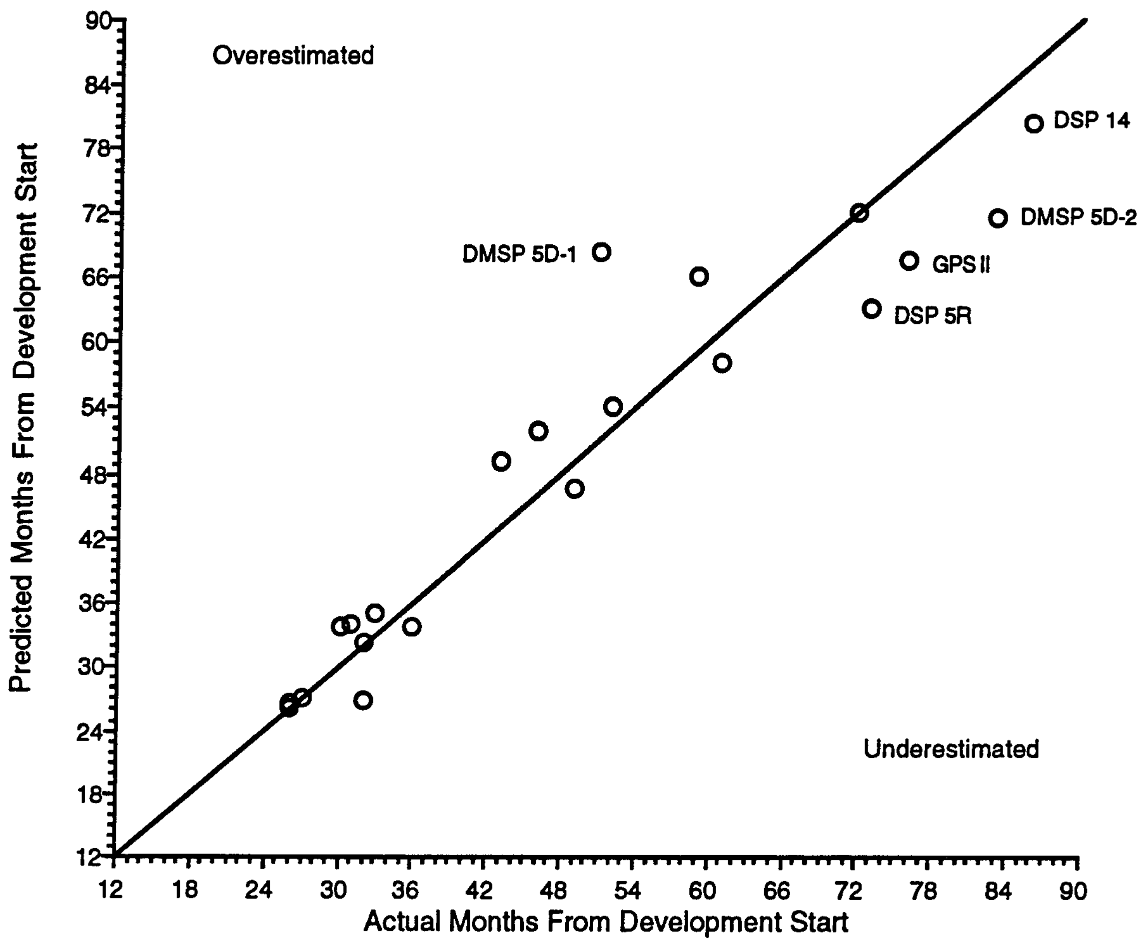


Figure IV-3. Equation 2.0 Predicted Versus Actual Months From Development Start to First Delivery

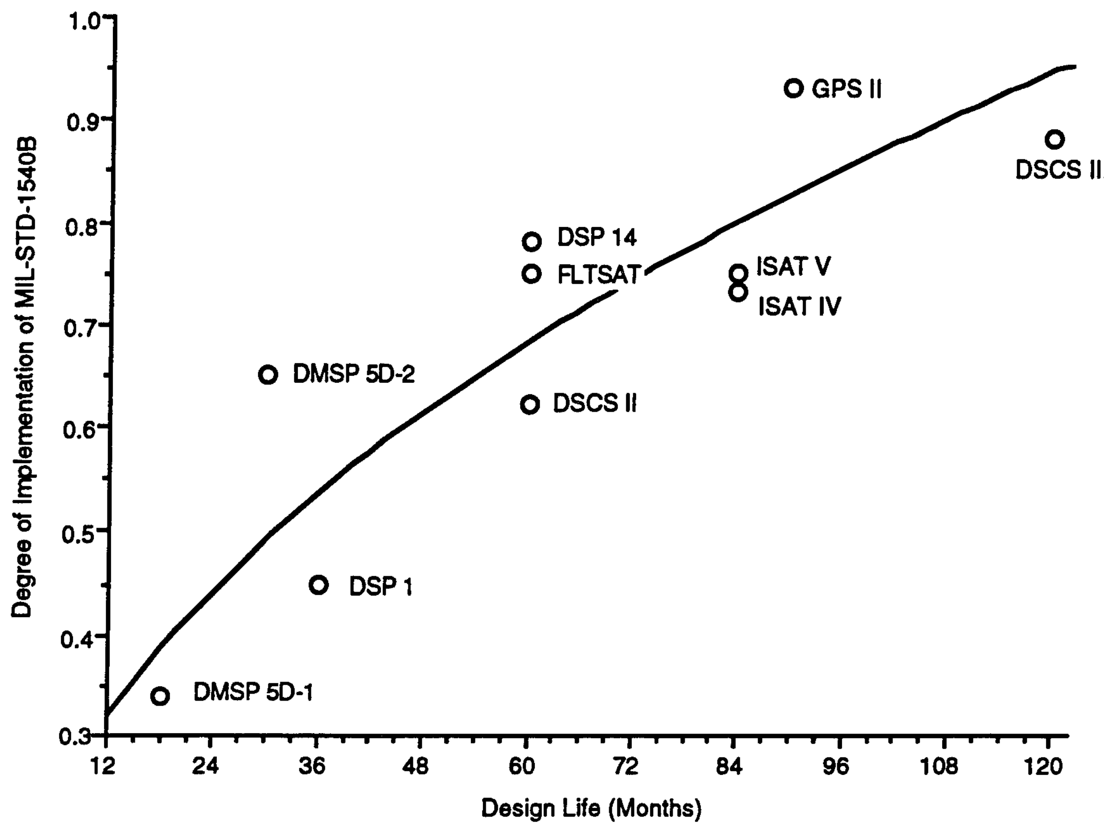
By removing the planetary spacecraft from the sample, we decrease the prediction error of the equation; SEE drops from .166 to .127. This is not surprising given the more homogenous data sample. Parameter estimates are relatively stable; the only pronounced difference is the parameter estimate for BOL Power. The pattern of residuals still leaves something to be desired; again the modification programs with longer durations are underestimated.

Table IV-3. Equation 2.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
AEM-HCMM	32	26.8	5.2	1.20
AE-C	26	26.0	0.0	1.00
DMSP 5D-1	51	68.1	-17.1	0.75
DMSP 5D-2	83	71.4	11.6	1.16
DSCS II	30	33.8	-3.8	0.89
DSCS III	52	54.0	-2.0	0.96
DSP 1	46	51.9	-5.9	0.89
DSP 14	86	80.4	5.6	1.07
DSP 5R	73	63.1	9.9	1.16
FLTSAT	61	58.1	2.9	1.05
GPS I	43	49.2	-6.2	0.87
GPS II	76	67.5	8.5	1.13
HEAO	59	66.1	-7.1	0.89
ISAT IV	26	26.5	-0.5	0.98
ISAT IVA	27	27.0	0.0	1.00
ISAT V	49	46.6	2.4	1.05
NATO III	36	33.7	2.3	1.07
P-72-2	32	32.2	-0.2	0.99
SBS	33	35.1	-2.1	0.94
SCATHA	31	34.0	-3.0	0.91
TDRSS	72	71.9	0.1	1.00

When the more homogenous data sample is used, additional independent variables are statistically significant. The most important of these is spacecraft design life (DESLIF). Design life implies higher power margins and additional propellant to sustain orbit altitude. For sensor spacecraft, longer design life also means higher-capacity active cooling for sensor arrays. In addition, longer design life implies more reliable parts and more rigorous testing at both the component and system level. The latter attribute is illustrated in Figure-IV-4, which shows spacecraft design life plotted against an index of test thoroughness, the degree of implementation of MIL-STD-1540B.[4] This index is a composite which reflects both qualification and acceptance testing. The complete series of test indices are presented in Appendix C. We would expect the time required to manufacture and test both the qualification model and the first flight-model spacecraft to increase with increased design life.

4 The test thoroughness index is presented in Reference [14].



$$\text{Index} = 0.0993 \times \text{Design Life}^{.471}$$
$$R^2 = 0.7$$

Figure IV-4. Design Life Versus Composite Test Thoroughness

In addition to design life, we found one other independent variable to be statistically significant, the experimental/scientific spacecraft dummy variable (EXPR). The estimating relationship with both DESLIF and the EXPR variable included is presented in equation-2.1.

$$\text{1stDEL} = .637\ \underset{(.01)}{(\text{BOL Power})^{.508}}\ \underset{(.04)}{(\text{DESLIF})^{.177}}\ \underset{(.01)}{1.585^{(\text{SENSOR})}}\ \underset{(.04)}{1.513^{(\text{NAV})}} \tag{2.1}$$

$$\underset{(.02)}{.751^{(\text{COMMER})}}\ \underset{(.01)}{1.381^{(\text{EXPR})}}$$

N = 21 $R^2 = .93$ Adjusted $R^2 = .90$ SEE = .116 Intercept adjustment = 1.007

Figure IV-5 shows values predicted by equation 2.1 plotted against program actuals. Table IV-4 summarizes the prediction errors associated with fitting the equation to the data.

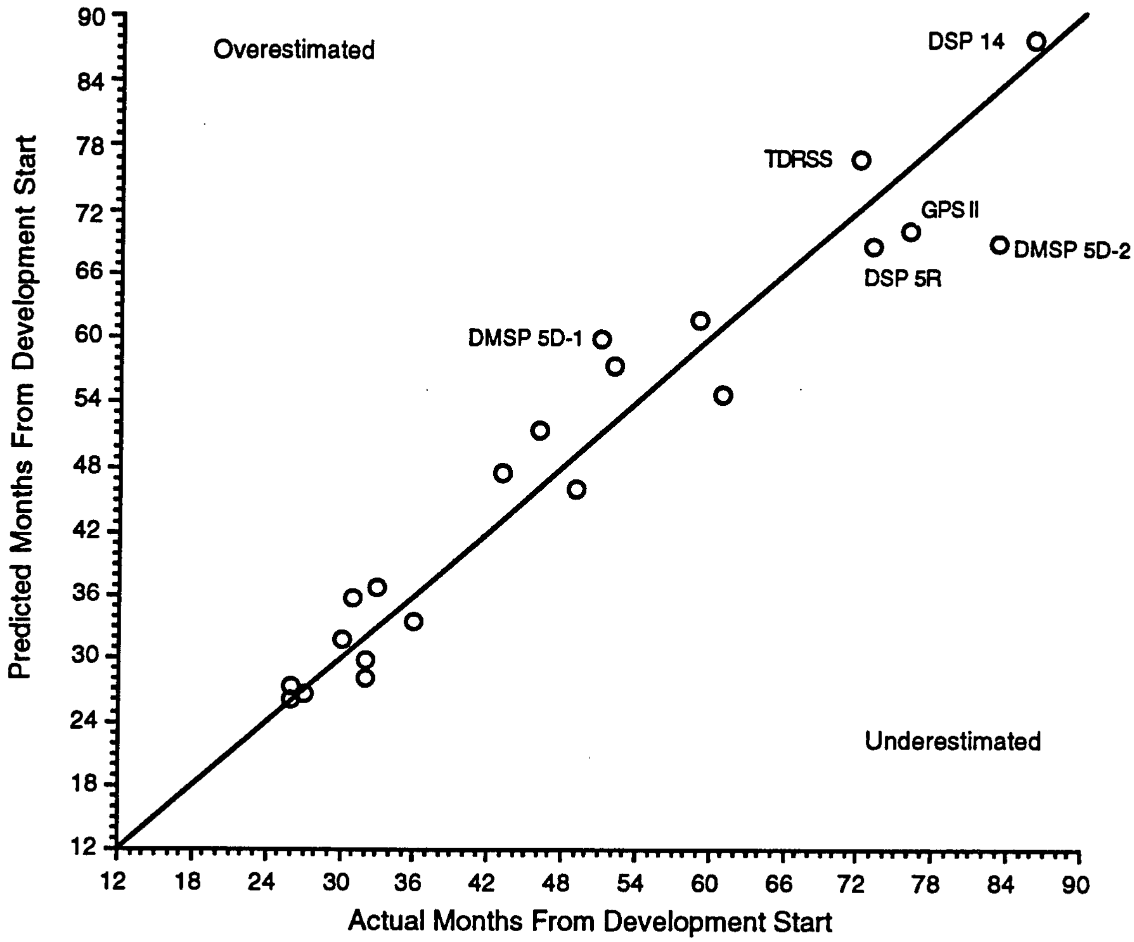


Figure IV-5. Equation 2.1 Predicted Versus Actual Months From Development Start to First Delivery

In equation 2.1, DESLIF is significant at the .04 level; DESLIF is only significant when EXPR is also included in the equation. The coefficient on the SENSOR dummy variable increases from 1.371 to 1.585. There is a negative relationship between DESLIF and SENSOR; the average design life for sensor spacecraft in the sample is 25.2 months compared with 87.8 months for the remaining spacecraft. Engineering knowledge and the data indicate that longer design lives are more difficult to achieve for sensor spacecraft than for other types; thus, when we account for design life in our estimating relationship, the coefficient on the SENSOR dummy variable increases.

By including DESLIF, equation 2.1 does a better job of estimating the sensor spacecraft modification programs. Extension of design life was often an important goal of the modification programs; from the DSP 1 to the DSP 5R/6R, design life was extended from 36 to 60 months and from the DMSP 5D-1 to the DMSP 5D-2, design life was extended from 18 to 30 months.

Table IV-4. Equation 2.1 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
AEM-HCMM	32	27.9	4.1	1.15
AE-C	26	27.1	-1.1	0.96
DMSP 5D-1	51	59.4	-8.4	0.86
DMSP 5D-2	83	68.2	14.8	1.22
DSCS II	30	31.5	-1.5	0.95
DSCS III	52	57.0	-5.0	0.91
DSP 1	46	51.0	-5.0	0.90
DSP 4	86	86.8	-0.8	0.99
DSP 5R	73	68.1	4.9	1.07
FLTSAT	61	54.3	6.7	1.12
GPS I	43	47.0	-4.0	0.91
GPS II	76	69.5	6.5	1.09
HEAO	59	61.2	-2.2	0.96
ISAT IV	26	25.9	0.1	1.00
ISAT IVA	27	26.4	0.6	1.02
ISAT V	49	45.6	3.4	1.07
NATO-III	36	33.3	2.7	1.08
P-72-2	32	29.7	2.3	1.08
SBS	33	36.5	-3.5	0.90
SCATHA	31	35.5	-4.5	0.87
TDRSS	72	76.0	-4.0	0.95

The coefficient on the EXPR variable indicates that experimental/scientific programs take 38% longer than other programs for otherwise equivalent spacecraft. Intuition tells us that the experimental/scientific spacecraft represent technically more ambitious or novel designs, so development time would be longer. However, the shorter design lives associated with experimental/scientific spacecraft would tend to result in estimates for a "typical" experimental/scientific spacecraft very close to those for an operational sensor spacecraft of similar power. In fact, the EXPR dummy variable is only significant when DESLIF is also in the equation. All but one of the experimental/scientific programs has NASA involvement; however, when EXPR is replaced with the NASA E.O. variable, model fit is inferior.

With the inclusion of the DESLIF and EXPR variables in estimating relationships derived from a more homogenous database, we were able to account for important phenomena while improving the overall fit of the models. The exclusion of the HST from the database and evidence about how poorly the models predict for very large (very high-powered) spacecraft means that application of the estimating relationships should be restricted to spacecraft that have BOL power similar to the spacecraft in the database.

c. Operational Spacecraft

The database for operational spacecraft includes the total database less the experimental/scientific spacecraft. Equation 3.0 presents an estimating relationship with the equivalent specification used in equations 1.0, 1.1, and 2.0.

$$1stDEL = .857\ (BOL\ Power)^{\underset{(.01)}{.577}}\ \underset{(.01)}{1.368}^{(SENSOR)}\ \underset{(.01)}{1.519}^{(NAV)}\ \underset{(.02)}{.767}^{(COMMER)} \qquad [3.0]$$

N = 16 $R^2 = .89$ Adjusted $R^2 = .85$ SEE = .131 Intercept adjustment = 1.009

Figure IV-6 shows values predicted by equation 3.0 plotted against program actuals. Table IV-5 summarizes the prediction errors associated with fitting the equation to the data.

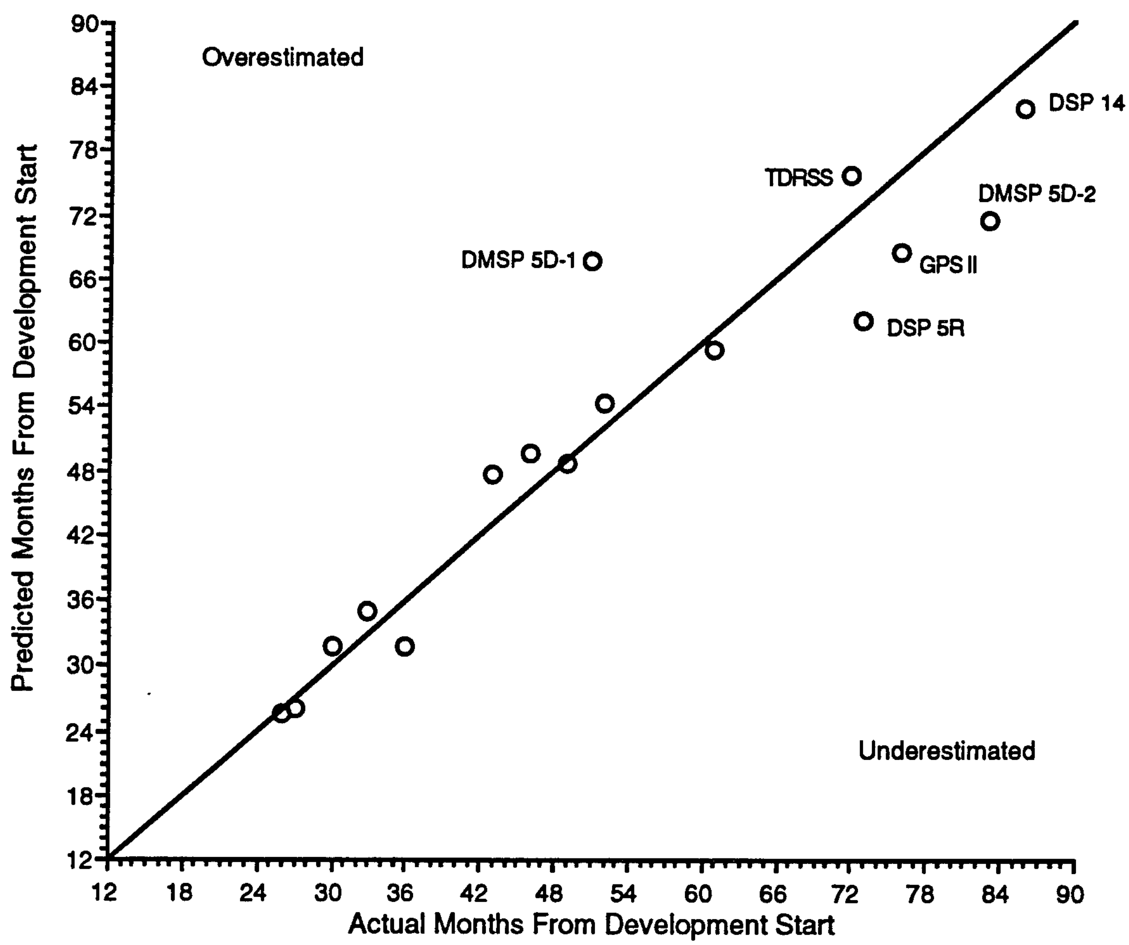


Figure IV-6. Equation 3.0 Predicted Versus Actual Months From Development Start to First Delivery

Table IV-5. Equation 3.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
DMSP 5D-1	51	68.4	-17.4	0.75
DMSP 5D-2	83	72.2	10.8	1.15
DSCS II	30	32.1	-2.1	0.93
DSCS III	52	54.9	-2.9	0.95
DSP 1	46	50.0	-4.0	0.92
DSP 14	86	82.6	3.4	1.04
DSP 5R	73	62.6	10.4	1.17
FLTSAT	61	59.8	1.2	1.02
GPS I	43	48.1	-5.1	0.89
GPS II	76	69.1	6.9	1.10
ISAT IV	26	25.7	0.3	1.01
ISAT IVA	27	26.3	0.7	1.03
ISAT V	49	49.1	-0.1	1.00
NATO III	36	32.0	4.0	1.12
SBS	33	35.4	-2.4	0.93
TDRSS	72	76.3	-4.3	0.94

Parameter estimates are similar to those for the equations with equivalent specifications, with a somewhat larger coefficient on BOL power. Included in the database are DoD and commercial communications spacecraft, a single NASA operational communications spacecraft (TDRSS) and DoD navigation and sensor spacecraft. One disadvantage of using the operational database is that there are no lower-powered spacecraft (BOL power < 500 watts) in the sample. Being able to confidently estimate programs for smaller lower-powered spacecraft is important for BMDO because of the inclusion of a small, lower-powered spacecraft, Brilliant Pebbles, in proposed system architectures.

As we have seen in previous analyses, the DSP 5R/6R, DSP 14, DMSP 5D-2, and GPS II programs are underestimated by equation 3.0, while the DMSP 5D-2 is greatly overestimated. As before, we find that we can improve the fit for these programs by adding the design life variable to the estimating relationship. The augmented estimating relationship is presented in equation 3.1.

$$\underset{}{\text{1stDEL}} = .510\,(\text{BOL Power})^{\underset{(.01)}{.537}}\,(\text{DESLIF})^{\underset{(.09)}{.180}}\,\underset{(.01)}{1.588}^{(\text{SENSOR})}\,\underset{(.01)}{1.532}^{(\text{NAV})}\,\underset{(.01)}{.756}^{(\text{COMMER})} \quad \textbf{[3.1]}$$

N = 16 $R^2 = .92$ Adjusted $R^2 = .88$ SEE = .118 Intercept adjustment = 1.007

Less colinearity is evident between BOL Power and DESLIF in the operational database than is evident in the larger Earth-orbiting database. We eliminated any interaction between DESLIF and EXPR. DESLIF's parameter estimate proved to be very stable between equations 2.1 and 3.1 (.177 versus .180). These factors provide additional confidence in the parameter estimate. Figure IV-7 shows values predicted by equation 3.0 plotted against program actuals. Table IV-6 summarizes the prediction errors associated with fitting the equation to the data.

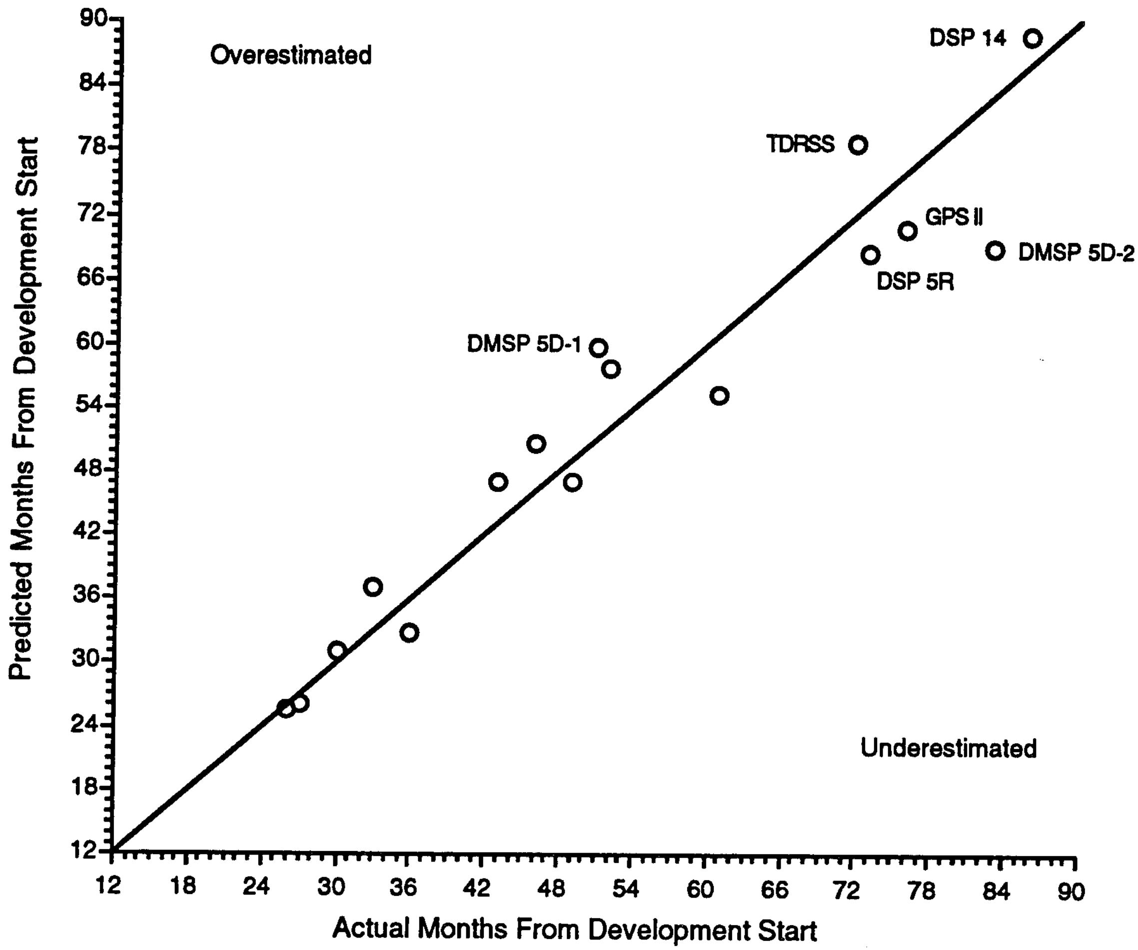


Figure IV-7. Equation 3.1 Predicted Versus Actual Months From Development Start to First Delivery

d. Earth-Orbiting Sensor Spacecraft

Because all major space systems proposed for strategic defenses are Earth-orbiting sensor spacecraft, we derived a set of estimating equations from a database consisting solely of such spacecraft. We estimated models both with and without the HST. Although this limits the data sample to 10 or 11 observations, we no longer need to use up degrees of freedom with dummy variables distinguishing spacecraft type.

Table IV-6. Equation 3.1 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
DMSP 5D-1	51	59.8	-8.8	0.85
DMSP 5D-2	83	69.0	14.0	1.20
DSCS II	30	31.0	-1.0	0.97
DSCS III	52	57.8	-5.8	0.90
DSP 1	46	50.6	-4.6	0.91
DSP 14	86	88.5	-2.5	0.97
DSP 5R	73	68.4	4.6	1.07
FLTSAT	61	55.3	5.7	1.10
GPS I	43	46.9	-3.9	0.92
GPS II	76	70.7	5.3	1.08
ISAT IV	26	25.7	0.3	1.01
ISAT IVA	27	26.2	0.8	1.03
ISAT V	49	46.9	2.1	1.05
NATO II	36	32.8	3.2	1.10
SBS	33	36.9	-3.9	0.89
TDRSS	72	78.5	-6.5	0.92

Equation 4.0 presents an estimating relationship derived from the sample that includes the HST.

$$\text{1stDEL} = 2.618\ (\text{BOL Power})^{.455} \quad [4.0]$$
$$(.01)$$

N = 11 $R^2 = .88$ Adjusted $R^2 = .87$ SEE = .152 Intercept adjustment = 1.012

Figure IV-8 shows a plot of the relationship between time to first delivery and BOL Power for equation 4.0. Table IV-7 summarizes the prediction errors associated with fitting the equation to the data.

Residual patterns for equation 4.0 are similar to those for equation 1.0, where the HST was also included in the database.

Equation 4.1 uses the same model specification as equation 4.0 but was estimated from the database without the HST.

$$\text{1stDEL} = 2.295\ (\text{BOL Power})^{.479} \quad [4.1]$$
$$(.01)$$

N = 10 $R^2 = .85$ Adjusted $R^2 = .83$ SEE = .156 Intercept adjustment = 1.012

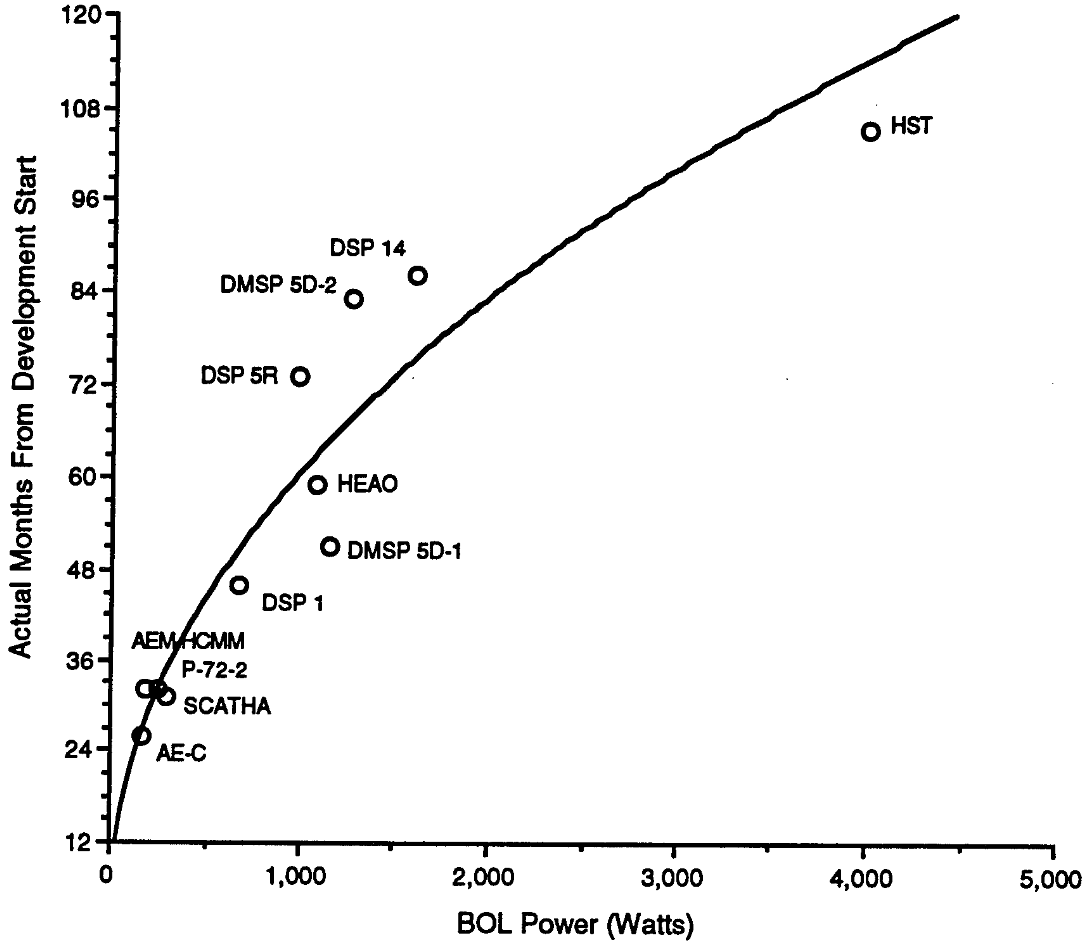


Figure IV-8. BOL Power Versus Months From Development Start to First Delivery: All Earth-Orbiting Sensor Spacecraft

Table IV-7. Equation 4.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
AEM-HCMM	32	28.2	3.8	1.14
AE-C	26	27.4	-1.4	0.95
DMSP 5D-1	51	65.6	-14.6	0.78
DMSP 5D-2	83	68.4	14.6	1.21
DSP 1	46	51.2	-5.2	0.90
DSP 14	86	76.1	9.9	1.13
DSP 5R	73	61.2	11.8	1.19
HEAO	59	63.8	-4.8	0.92
HST	105	115.5	-10.5	0.91
P-72-2	32	33.3	-1.3	0.96
SCATHA	31	35.0	-4.0	0.89

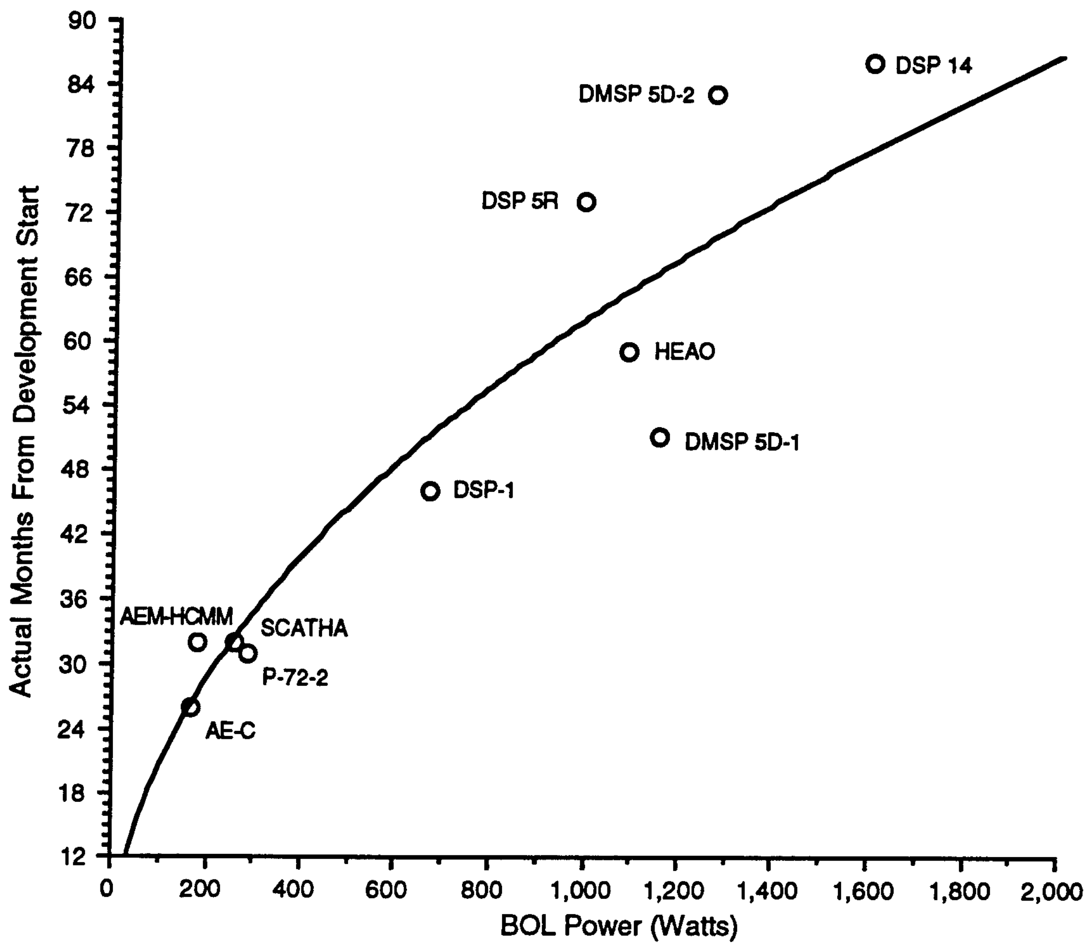


Figure IV-9. BOL Power Versus Months From Development Start to First Delivery: All Earth-Orbiting Sensor Spacecraft Less HST

Table IV-8. Equation 4.1 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
AEM-HCMM	32	27.6	4.4	1.16
AE-C	26	26.9	-0.9	0.97
DMSP 5D-1	51	67.3	-16.3	0.76
DMSP 5D-2	83	70.4	12.6	1.18
DSP 1	46	51.9	-5.9	0.89
DSP 14	86	78.7	7.3	1.09
DSP 5R	73	62.6	10.4	1.17
HEAO	59	65.4	-6.4	0.90
P-72-2	32	33.0	-1.0	0.97
SCATHA	31	34.7	-3.7	0.89

Dropping the HST from the database affects the parameter estimates only slightly, while the prediction error is essentially unchanged. Figure IV-9 shows a plot of the relationship between time to first delivery and BOL Power for equation 4.1. Table IV-8 summarizes the prediction errors associated with fitting the equation to the data.

When we tried estimating equations 4.0 and 4.1 augmented with the design life and experimental/scientific variables, DESLIF and EXPR were not statistically significant. In the case of equation 4.0, this may be due to the inclusion of the HST in the database. At 180 months, the HST has the longest design life in the sample. However, the HST's design life is not directly comparable to the design life of the other spacecraft because it was specifically designed to be periodically serviced by the Space Shuttle. For equation 4.1, the insignificance of the parameter estimates may be because of two reasons. With a data sample of 10 data points, we are left with only six degrees of freedom when we include DESLIF and EXPR in the estimating relationship. Related to this limitation is a high degree of colinearity between DESLIF and BOL Power. The correlation coefficient between BOL Power and DESLIF is .63, which is higher than in the other data samples.

The standard errors for equations 4.0 and 4.1 are higher than for equations of equivalent specification derived from other data samples. The sensor spacecraft are the most heterogeneous group of spacecraft in our sample. Because numerous types of sensor and instrument packages are included, the relationship between spacecraft power and spacecraft complexity, and thus development schedule, is bound to be the least consistent.

e. Operational Communications Spacecraft

Operational communications spacecraft represent the most homogeneous data category in our database. We estimated a single time-estimating relationship that yields the best fit of any of our TERs. The independent variables include BOL Power and the commercial dummy variable. The estimating relationship is presented in equation 5.0.

$$\text{1stDEL} = 1.140\ (\text{BOL Power})^{.535}\ .767^{(\text{COMMER})} \quad [5.0]$$
$$\qquad\qquad\qquad (.01)\quad (.01)$$

N = 9 R^2 = .98 Adjusted R^2 = .98 SEE = .065 Intercept adjustment = 1.002

Design life did not prove to be statistically significant in this data set. There is less variability in design life for the sample of communications spacecraft than in the database as a whole. Figure IV-10 shows a plot of the relationship between time to first delivery and BOL Power for equation 5.0. Table IV-9 summarizes the prediction errors associated with fitting the equation to the data.

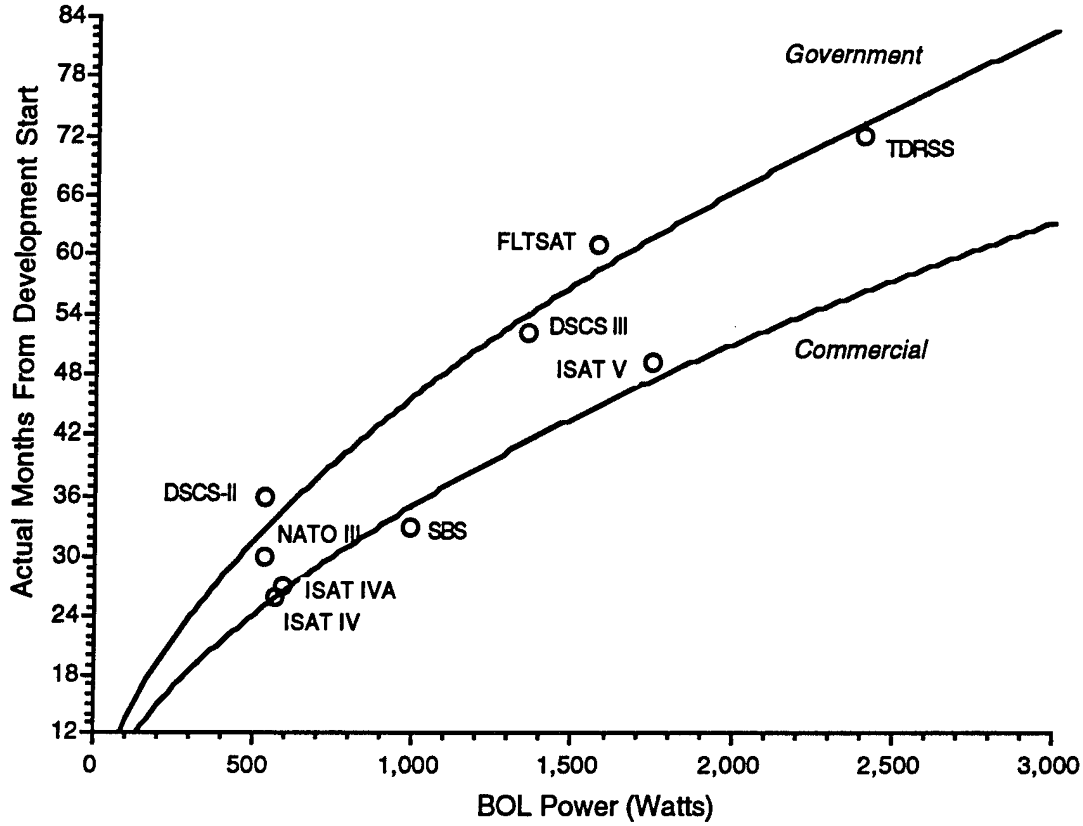


Figure IV-10. BOL Power Versus Months From Development Start to First Delivery: Communications Spacecraft

Table IV-9. Equation 5.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
DSCS II	30	32.8	-2.8	0.91
DSCS III	52	54.0	-2.0	0.96
FLTSATSAT	61	58.5	2.5	1.04
ISAT IV	26	26.0	0.0	1.00
ISAT IVA	27	26.5	0.5	1.02
ISAT V	49	47.3	1.7	1.03
NATO III	36	32.8	3.2	1.10
SBS	33	35.0	-2.0	0.94
TDRSS	72	73.3	-1.3	0.98

The relationship between BOL Power and mission performance and complexity is most direct for communications spacecraft. Increasing the number and power of communications transponders directly affects electrical power requirements.

f. Disaggregated Intervals

We had less success estimating intervals at a more disaggregated level than time to first flight-model delivery. Here we give two estimating relationships: one for months from development start to CDR and another for months from CDR to delivery of the first flight-model spacecraft. The spacecraft in the database included the full database less the NASA scientific spacecraft, two large outliers (DSP 1 and DMSP 5D-2) and three spacecraft with missing data (ISAT IV, ISAT V and DSP 5R). This left a data sample of eleven observations. Unexplained variability for the NASA data points is very large. One discernible trend in the NASA data when compared to DoD or commercial programs was for more time to elapse before CDR. The NASA programs often had multiple CDRs due to requirements and design changes. The DMSP 5D-2 was a large outlier on the low side (7 months) while the DSP 1 was an outlier on the high side (24 months). In deriving an estimating relationship, we found that BOL Power was the only statistically significant independent variable. The estimating relationship is presented in equation 6.0. Neither the spacecraft type or design life independent variables were statistically significant.

$$\text{Months to CDR} = 1.809\ (\text{BOL Power})^{\underset{(.01)}{.311}} \qquad [6.0]$$

N = 11 R^2 = .45 Adjusted R^2 = .39 SEE = .208 Intercept adjustment = 1.022

Figure IV-11 shows a plot of the relationship between time to first delivery and BOL Power for equation 6.0. Table IV-10 summarizes the prediction errors associated with fitting the equation to the data.

Although the estimating relationship explains only 45 percent of the variability in time to CDR, the relatively small amount of variability in the interval (for our data sample) means that the resulting SEE (.208) is reasonable for estimating purposes.

The same data sample used for equation 6.0 was is used in estimating the model for months from CDR to first delivery. The estimating relationship is presented in equation 7.0.

$$\text{Months from CDR to 1stDEL} = .110\ (\text{BOL Power})^{\underset{(.01)}{.778}}\ 2.067^{\underset{(.05)}{(\text{SENSOR})}}\ 2.447^{\underset{(.01)}{(\text{NAV})}} \qquad [7.0]$$

N = 11 R^2 = .88 Adjusted R^2 = .83 SEE = .230 Intercept adjustment = 1.027

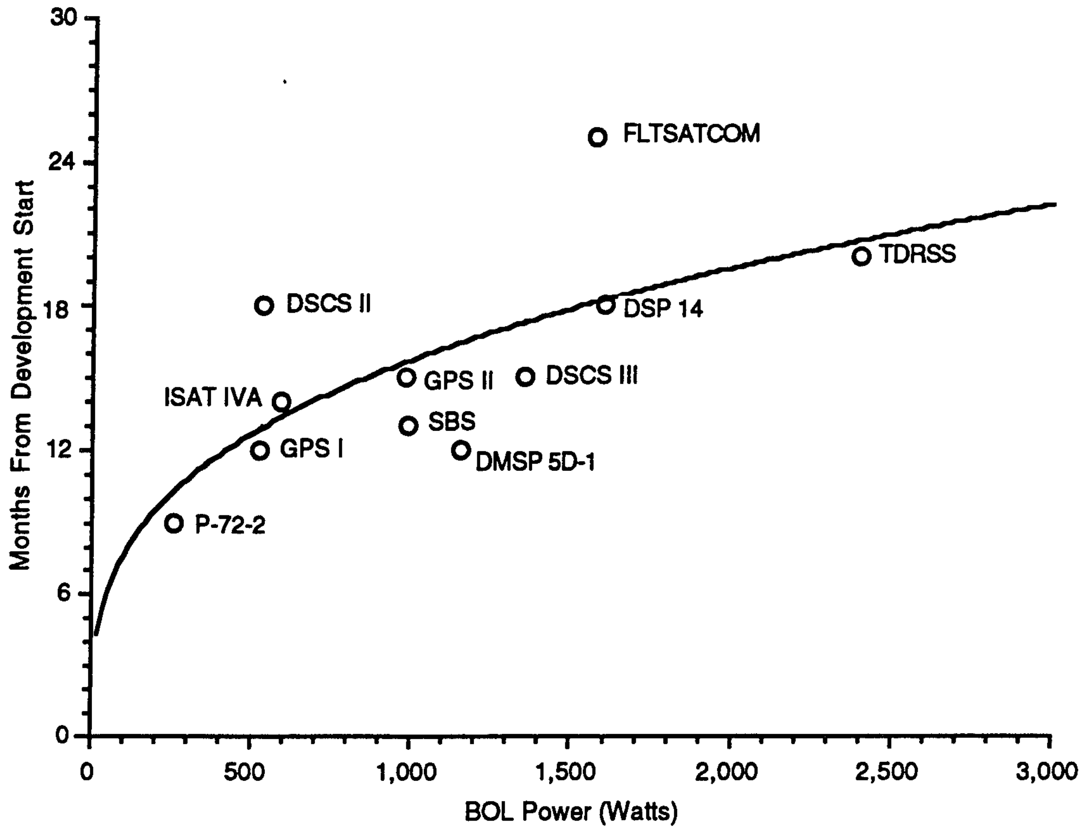


Figure IV-11. BOL Power Versus Months From Development Start to CDR

Table IV-10. Equation 6.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
DMSP 5D-1	12	16.5	-4.5	0.73
DSCS II	18	12.9	5.1	1.39
DSCS III	15	17.3	-2.3	0.87
DSP 14	18	18.2	-0.2	0.99
FLTSATSAT	25	18.1	6.9	1.38
GPS I	12	12.8	-0.8	0.93
GPS II	15	15.6	-0.6	0.96
ISAT IVA	14	13.3	0.7	1.05
P-72-2	9	10.3	-1.3	0.87
SBS	13	15.7	-2.7	0.83
TDRSS	20	20.7	-0.7	0.97

Design life did not prove to be statistically significant in this sample; colinearity between DESLIF, BOL Power, and the sensor dummy variable is very high. In estimating the time from CDR until first delivery, we found that the parameter estimates for the spacecraft type dummy variables were of larger magnitude than those estimated for the full interval to first delivery. The parameter estimate for BOL Power is also considerably larger. That the parameter estimates are larger is intuitive given the relatively small parameter estimate for BOL Power and the absence of the spacecraft type variables in the CDR equation. However, given that on average (for this sample) the time from CDR to first delivery accounts for 69% of the full interval, the large divergence in parameter estimates from those for the full interval is not reassuring. Figure IV-12 shows the values predicted by equation 7.0 plotted against program actuals. Table IV-11 summarizes the prediction errors associated with fitting the equation to the data.

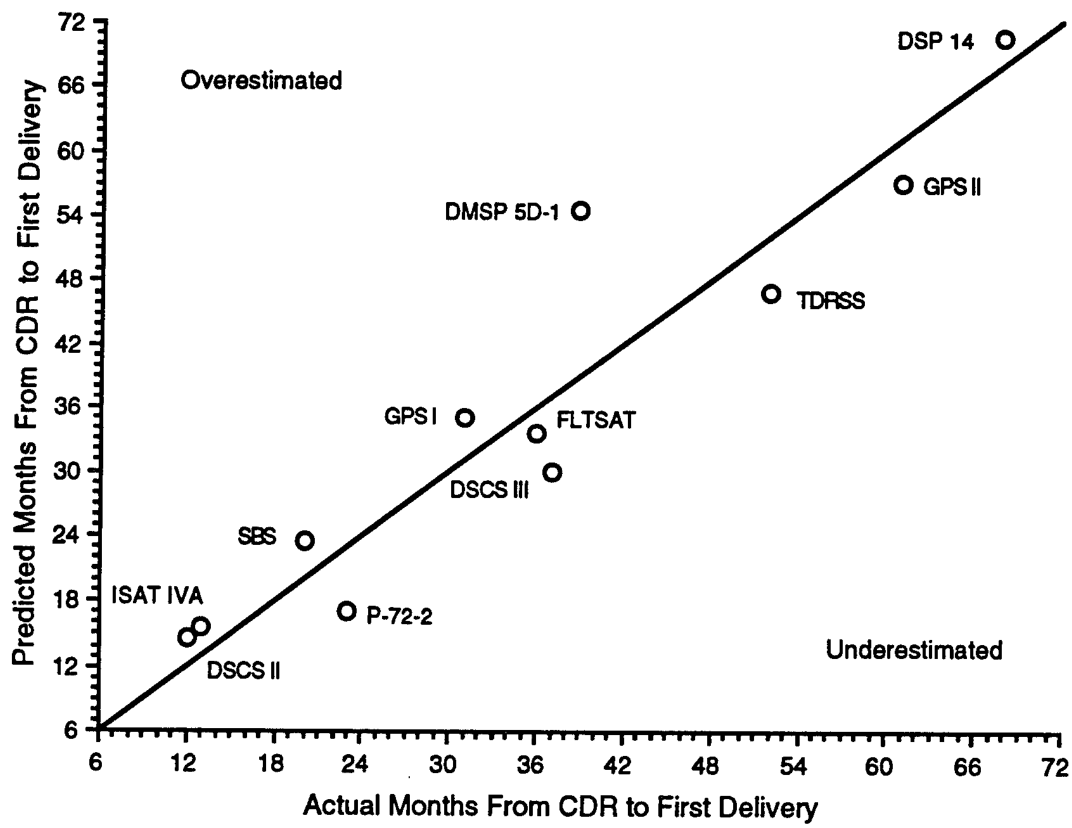


Figure IV-12. Equation 7.0 Predicted Versus Actual Months From Development Start to First Delivery

A possible interpretation of the results at the disaggregated level is that the additional development time associated with sensor and navigation spacecraft occurs while the qualification and flight hardware is being built (post-CDR) and not during the design phase of the program (pre-CDR).

Table IV-11. Equation 7.0 Prediction Error Summary

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
DMSP 5D-1	39	53.5	-14.5	0.73
DSCS II	12	14.2	-2.2	0.84
DSCS III	37	29.4	7.6	1.26
DSP 14	68	69.1	-1.1	0.98
FLTSATSAT	36	33.0	3.0	1.09
GPS I	31	34.3	-3.3	0.90
GPS II	61	55.9	5.1	1.09
ISAT IVA	13	15.4	-2.4	0.85
P-72-2	23	16.8	6.2	1.37
SBS	20	23.0	-3.0	0.87
TDRSS	52	45.8	6.2	1.14

3. Observations

Although the description of such a large number of estimating relationships may seem monotonous or repetitive, the objective is to supply the reader with insights into the data analysis process and the various relationships within the data. Such insights should prove beneficial to analysts in their application of the TERs presented in this chapter.

The data segmentation schemes allowed us to test the stability of parameter estimates across different data samples. We found a great deal of consistency in the parameter estimates across data samples. BOL Power proved to be a very powerful explanatory variable with relatively stable parameter estimates. The spacecraft and customer type variables also had strong and regular effects. Design life proved important in explaining errors for important outlying observations.

C. SPACECRAFT MANUFACTURING

In analyzing spacecraft production, we examined data for manufacturing schedule intervals from fabrication start to acceptance test completion for flight-model spacecraft in series production. The data are presented in Chapter III. Because acceptance test completion is the common milestone available for all of our production units, we measured manufacturing times (ManTime) backwards from this milestone to all other manufacturing milestones for each production unit. This allowed for maximum use of the data we had collected. Using this definition of ManTime and the definition previously given for development time, we saw a clear overlap between our development and manufacturing milestones; the first spacecraft in the manufacturing series is the first flight-model spacecraft whose delivery marks the end of development.

1. Data Sample Description

We have data on nine spacecraft manufacturing programs. Within each program we have data on multiple spacecraft units and for each spacecraft unit we have data on a maximum of four milestones: time to completion of acceptance testing from (1) completion of system assembly, (2) start of system testing, (3) start of system assembly, and (4) start of system fabrication. In all we have 119 data points. In our regression analyses we use 1/0 dummy variables to distinguish between the four milestones.

Candidate schedule drivers not previously defined are:

- Spacecraft cumulative quantity (CumQ). The cumulative quantity associated with each spacecraft flight-unit. Where a qualification model was built before the first flight-unit (prototype development approach), the value of CumQ associated with the first flight-unit is 2.
- Acceptance test index (TINDEX). The degree of implementation of MIL-STD-1540B in acceptance testing. Data for TINDEX is presented in Appendix C.
- System assembly complete dummy variable (CAss). A dummy variable with a value of 1 if the interval characterized is the time from system assembly completion to acceptance test completion and a value of 0 otherwise.
- Acceptance test start dummy variable (STest). A dummy variable with a value of 1 if the interval characterized is the time from acceptance test start to acceptance test completion and a value of 0 otherwise.
- System assembly start dummy variable (CAss). A dummy variable with a value of 1 if the interval characterized is the time from system assembly start to acceptance test completion and a value of 0 otherwise.
- Major production delay (DELAY). A dummy variable with a value of 1 if the relevant spacecraft unit experienced an unusual schedule delay and 0 otherwise.

The DELAY variable accounts for large random production delays that affect individual spacecraft units. Although such delays do not occur often in the data, they are relatively large in magnitude. Because of the nature of interval length data, we did not observe schedule length decreases of similar magnitude; we can never observe negative interval lengths. Figure IV-13 illustrates the delay phenomena for the GPS II production program.

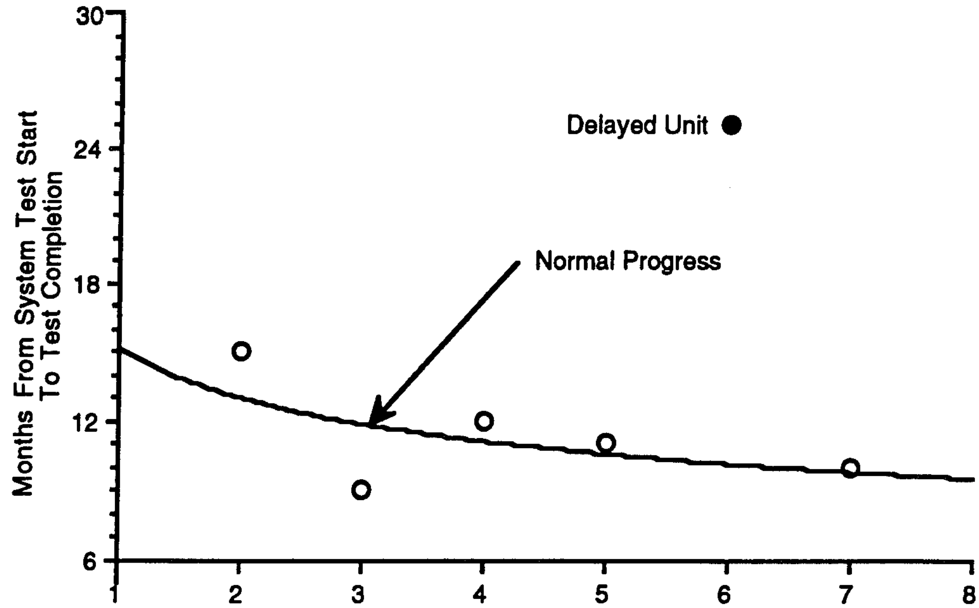


Figure IV-13. GPS II Manufacturing Delay Example

Although the GPS II is an extreme example, it illustrates the potential difficulties in estimating the parameters for manufacturing interval relationships. If we did not account for the delays the normality assumption for the distribution of regression residuals would have been violated. We introduced the DELAY variable into the regression analysis to eliminate the influence of the random delays on the regression coefficients. In Chapter V, we treat the program schedule effects of random production delays outside of the regression framework.

2. Time-Estimating Relationships

Due to the different number of spacecraft units in each production program and differences in data availability across production programs, the number of data observations vary widely across programs. This variation creates a problem in parameter estimation for those variables that describe spacecraft characteristics; the programs with a greater number of observations will influence the parameter estimates disproportionally. We attempted to address the problem by estimating spacecraft characteristic parameters using weighted least squares. For each program, we weighted each observation by the inverse of the number of observations for that program.

Using this procedure, we estimated an equation including BOL Power, TINDEX, and the SENSOR and NAV dummy variables. Although the parameter estimates were statistically significant, the estimate for BOL power was inconsistent with previous results and the parameter estimates were very sensitive to changes in the composition of the database. Although we have a total of 119 data points in the manufacturing database, there are only nine different spacecraft models and corresponding characteristic values. In effect, we are estimating five parameters (including the intercept) using only nine data points. The regression analysis clearly suffers from too few degrees of freedom.

In an alternative approach, we related manufacturing times for each spacecraft unit to the months from development start to first flight-model delivery. In estimating manufacturing times for a proposed system, we would first estimate time to first delivery using the appropriate equation from the overall development schedule section. In this modeling approach, months to first delivery is analogous to first-unit cost in a cost-progress curve relationship. Months to first delivery includes development activities before the start of hardware manufacturing. For this reason, the estimating relationship should include a proportional scaling factor to account for the additional time associated with these activities. Other variables should include CumQ to account for learning, the milestone dummy variables, and the DELAY dummy variable.

When we apply the milestone dummy variables, the baseline milestone interval is the number of months from fabrication start to assembly complete. Because this interval is logically the longest milestone interval in the data, the parameter estimates for the other milestone dummy variables should have parameter estimates of less than 1. Because the time from fabrication start to the completion of acceptance testing for the first flight-model spacecraft represents a significant proportion of a spacecraft's development schedule, we expected the proportional scaling factor on time to first delivery to be greater than .5 but less than 1. We also expected manufacturing times to decrease with cumulative quantity (negative coefficient on CumQ), that a progress curve exists for manufacturing time analogous to the cost progress curve. We expected the DELAY parameter estimate to be positive. Equation 8.0 presents the estimating relationship for manufacturing time.

$$\mathrm{ManTime} = .747\,(\mathrm{1stDEL})\,(\mathrm{CumQ})^{-.120}\ \underset{(.02)\ (.01)}{.274^{(\mathrm{CAss})}}\ \underset{(.01)}{.385^{(\mathrm{STest})}}\ \underset{(.01)}{.637^{(\mathrm{SAss})}}\ \underset{(.01)}{1.515^{(\mathrm{DELAY})}} \qquad [8.0]$$

N = 119 $R^2 = .72$ Adjusted $R^2 = .78$ SEE = .390 Intercept adjustment = 1.079

In order to estimate the specification using ordinary least squares, we restricted the parameter estimate on 1stDEL to 1, which gave us the desired equation form. We interpreted the intercept term as the proportional scaling factor on time to first delivery. Its value indicates that manufacturing time for the first spacecraft unit accounts for 75% of total development time. For programs with a prototype development approach, the first flight-model unit is actually the second spacecraft unit built. The parameter estimate on cumulative quantity corresponds to a learning curve of 92%. This is consistent with cost-progress curves reported for spacecraft programs.

The ordering of the parameters on the milestone interval dummy variables was as expected. For most of the spacecraft, system testing begins before the final mating of the payload and spacecraft bus is complete. This is the reason the parameter estimates indicate fewer months between acceptance test completion and system assembly than between acceptance test completion and system test start. The parameter estimate for DELAY indicates that on average delayed spacecraft units will take 1.5 times longer to produce than spacecraft units that do not experience major manufacturing schedule disruptions.

Figure IV-14 plots values predicted by equation 8.0 against program actuals. Table D-1 in Appendix D summarizes the prediction errors associated with fitting the equation to the data.

Because of the large disparity in the number of data points for each spacecraft model, there is no reason to expect the average of errors for each spacecraft model to be balanced between positive and negative values. Figure IV-15 plots average predicted values for each program against average actual values. Table IV-12 summarizes prediction errors for the program averages. Note that the distribution of milestone interval data across programs differs (e.g. one spacecraft may have more data available on fabrication starts than another), so differences in the average intervals between spacecraft models depends on more than the relative differences in overall manufacturing times between models.

In addition, we calculated analogous measures of model fit for program averages,

$$N = 9 \qquad K = 1 \qquad R^2 = .92 \qquad \text{Adjusted } R^2 = .92 \qquad SEE = .325$$

where K is the number of program-level parameters estimated. Because the only program-level parameter is the intercept term, the adjusted R^2 and the R^2 are the same. We see that the model fit for program averages is better than for individual spacecraft units. On average, we predict better for any given program; explaining variations in the manufacturing times for individual spacecraft units is more difficult.

As previously mentioned, the errors based on program averages are not balanced. However, it is simple to adjust the intercept so that the sum of the program average errors will be equal to zero. The method is analogous to the balance-adjustment factor (BAF), an intercept adjustment technique that is independent from the SEE measure and from assumptions about the distribution of the residuals [15]. We calculated an additional intercept adjustment factor of 1.062. The factor is in addition to the adjustment factor of 1.079 applied when we transformed the original equation from log space to arithmetic space. The resulting parameter estimate for the intercept is .793. By applying the additional intercept adjustment factor, we improved the measures of model fit for program averages slightly—R^2 increasing from .922 to .925. Because the intercept is the only program-specific variable, adjusting the intercept in this fashion is equivalent to estimating the intercept parameter using the weighted least-squares scheme previously outlined.

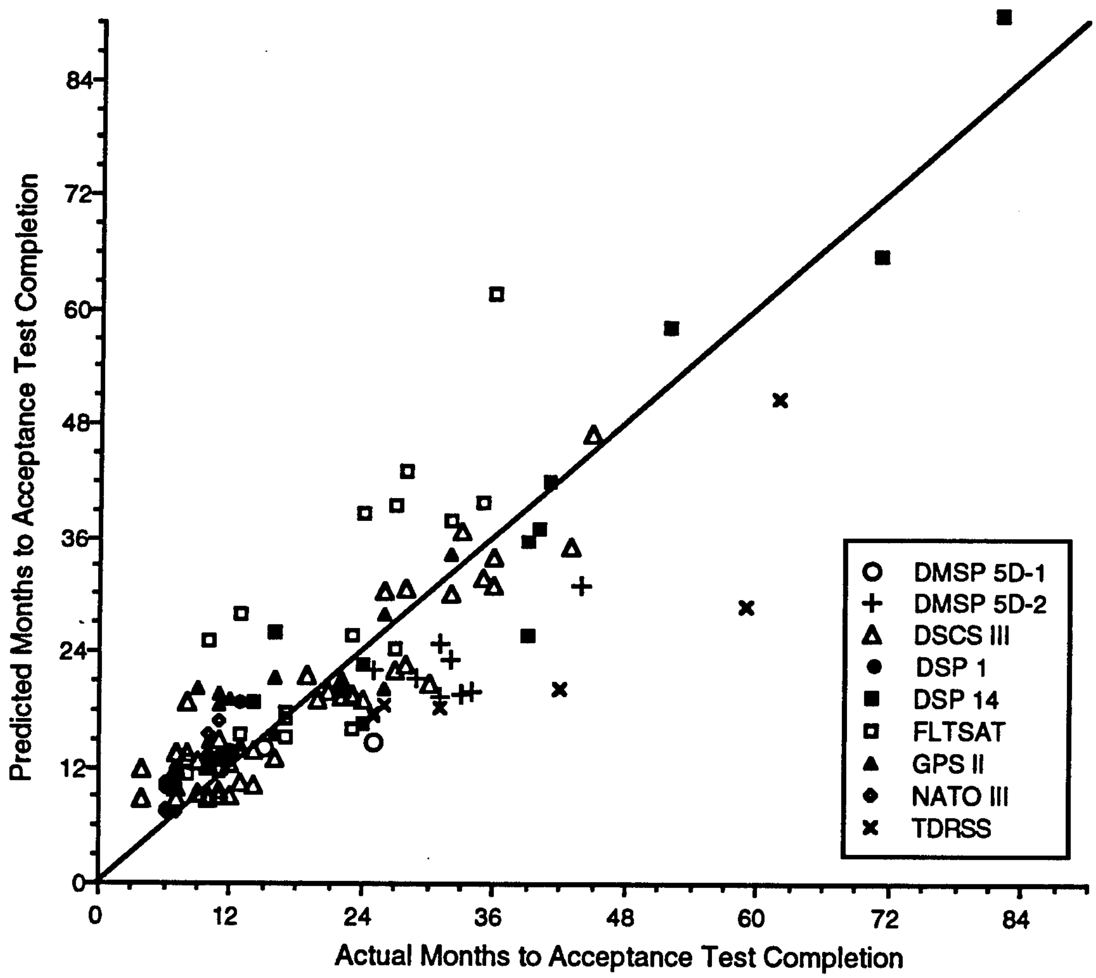


Figure IV-14. Equation 8.0 Predicted Versus Actual Months From Manufacturing Milestones to Acceptance Test Completion

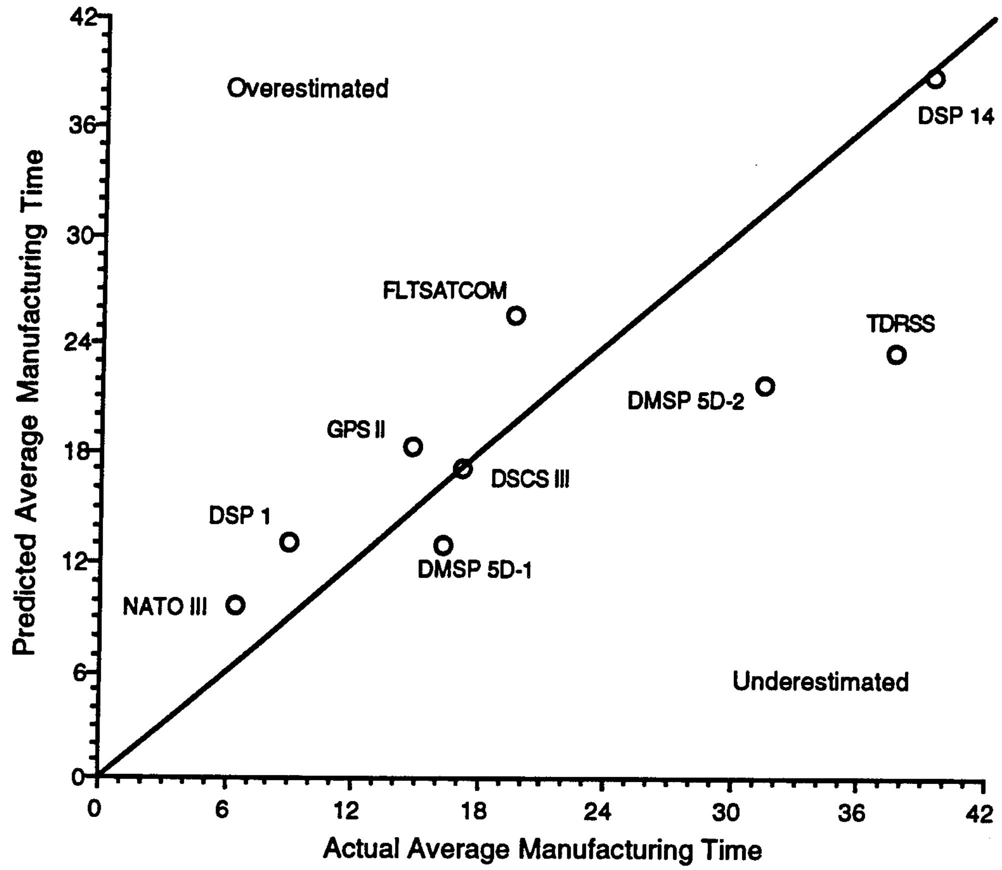


Figure IV-15. Equation 8.0 Predicted Versus Actual Average Manufacturing Times

Table IV-12. Equation 8.0 Prediction Error Summary: Average Across Programs

Spacecraft	Actual Value (Months)	Predicted Value (Months)	Error (Actual – Pred.)	Multiplicative Residual (Actual/Pred.)
DMSP 5D-1	16.3	12.9	3.4	1.26
DMSP 5D-2	31.4	21.6	9.8	1.45
DSCS III	17.2	17.1	0.1	1.01
DSP 1	9.0	13.0	-4.0	0.69
DSP 14	39.2	38.7	0.5	1.01
FLTSAT	19.5	25.6	-6.1	0.76
GPS II	14.8	18.3	-3.5	0.81
NATO III	6.4	9.6	-3.3	0.66
TDRSS	37.6	23.4	14.2	1.61

3. Observations

Results of the production analyses are intuitive and generally consistent with other results. Although the estimating error is large for reliably estimating any single manufacturing interval for a specific spacecraft unit, on average the estimating relationship is adequate. Analysts can simulate production schedules for future programs. The effects of the DELAY variable can be implemented through the manufacturing schedule simulation. Analysts can use manufacturing schedule simulations to test sensitivities to changes in certain assumptions. For example, for the proposed high-production-rate Brilliant Pebbles program, there has been discussion of performing full system testing only on randomly chosen units. The schedule effects of such an approach can be explored using manufacturing schedule simulations. Given a set of production rate scenarios, the total number of spacecraft in process at a given time can be estimated for each scenario. This estimate may provide insight into whether facilities are adequate to handle proposed production rates.

D. SOFTWARE

We defined the software development period as beginning with the preliminary design (PD) phase of the software CSCI and ending with the configuration item integration and testing (IT) phase. The PD phase is defined as beginning with system requirement review (SRR) or system design review (SDR).

1. Data Sample Description

The data sample used in our analysis contained 51 software development programs related to six space programs. Of the 51 data points, 12 were associated with manned missions, 26, with Earth-orbiting sensor spacecraft, and 13 had planetary missions. Development times measured in months are the dependent variables in regression analyses. The candidate schedule drivers include:

- Thousands of source line of code (KSLOC)
- Average staff level
- Ground-based software dummy variable (Ground). A dummy variable with a value of 1 for software based on the ground and a value of 0 otherwise. The remaining data points are for space-based software.

- System software dummy variable (System). A dummy variable with a value of 1 for system software and a value of 0 otherwise.
- Support software dummy variable (Support). A dummy variable with a value of 1 for support software and a value of 0 otherwise.

2. Time-Estimating Relationships

In developing a regression model to estimate software development duration in months, several different specifications were tested. Measures of software size, staff level, environment, and type of application proved to be good explanatory variables.

$$\text{Duration} = 28.46\,(\text{KSLOC})^{.661}\,(\text{Average Staff Level})^{-.586}\,.760^{(\text{System})}\,.270^{(\text{Ground})} \quad [9.0]$$

(.01) (.01) (.08) (.01)

$N = 51$ $R^2 = .63$ Adjusted $R^2 = .62$ SEE = .386 Intercept Adjustment = 1.077

The baseline case for equation 9.0 is space-based application software. The results are generally consistent with intuition: duration increases at a decreasing rate with lines of code; duration decreases at a decreasing rate as staff size increases; and space-based software requires a longer duration than ground-based software. The only counter-intuitive parameter estimate is the negative value for system software; because it is generally believed that system software is more difficult to develop than is application software, we expected the parametric estimate to be positive. The support software dummy variable was not statistically significant.

Figure IV-16 shows software development duration predicted by equation 9.0 plotted against CSCI actuals. Table D-1 in Appendix D summarizes the prediction errors associated with fitting the equation to the data.

The estimating relationship tends to underestimate those CSCIs with development times of around 36 months and underestimate those with longer times. The two outliers are mission design application software for a planetary mission and the mission control system software for a manned system. By excluding the two outliers from the data sample, we got an estimating relationship with a more pleasing pattern of residuals. The estimating relationship estimated with the outliers excluded is presented in equation 9.1.

$$\text{Duration} = 28.18\,(\text{KSLOC})^{.698}\,(\text{Average Staff Level})^{-.613}\,.693^{(\text{System})}\,.254^{(\text{Ground})} \quad [9.1]$$

(.01) (.01) (.02) (.01)

$N = 49$ $R^2 = .67$ Adjusted $R^2 = .66$ SEE = .364 Intercept Adjustment = 1.068

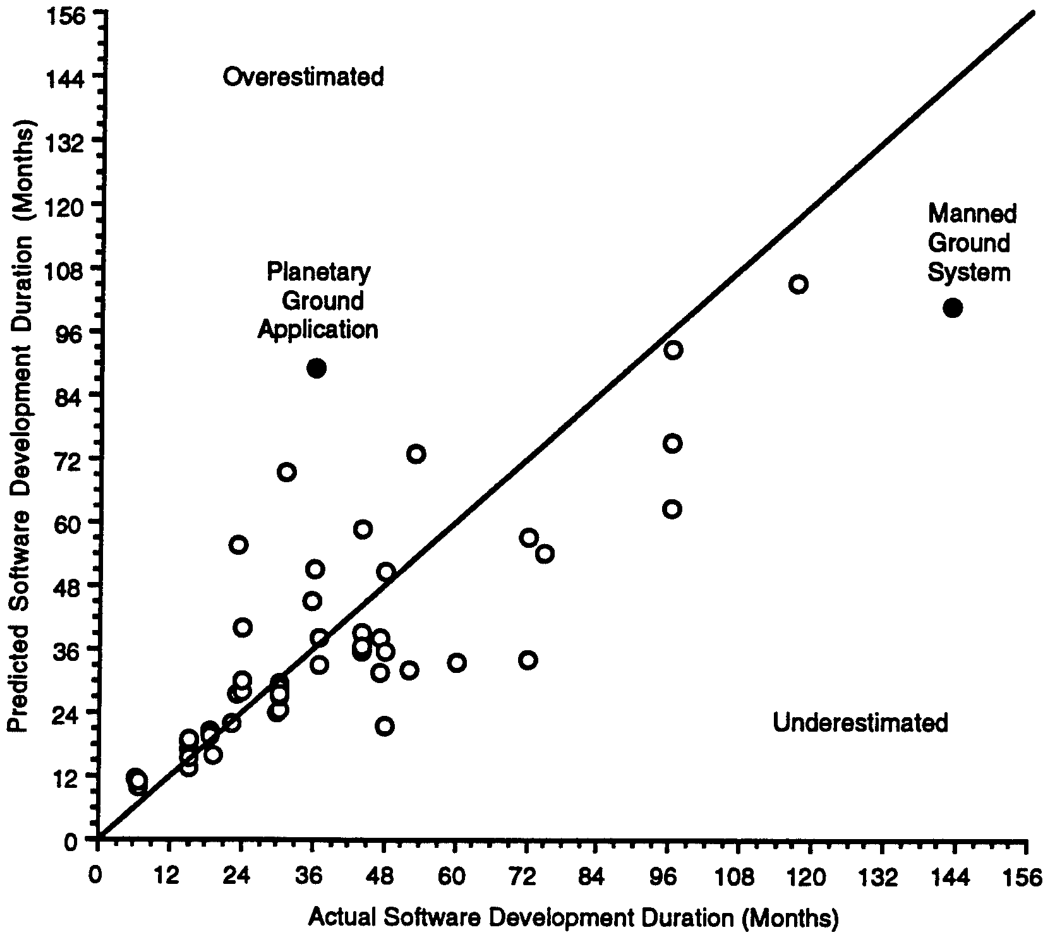


Figure IV-16. Equation 9.0 Predicted Versus Actual Software Duration

Model fit improved slightly and the statistical significance of the parameter estimate for system improved greatly. Figure IV-17 shows software development duration predicted by equation 9.1 plotted against CSCI actuals. Table D-3 in Appendix D summarizes the prediction errors associated with fitting the equation to the data.

3. Observations

Software development is a labor-intensive activity. Equations 9.0 and 9.1 are useful in checking the consistency of software development schedules with staffing plans. An example of such an application is given in Chapter V.

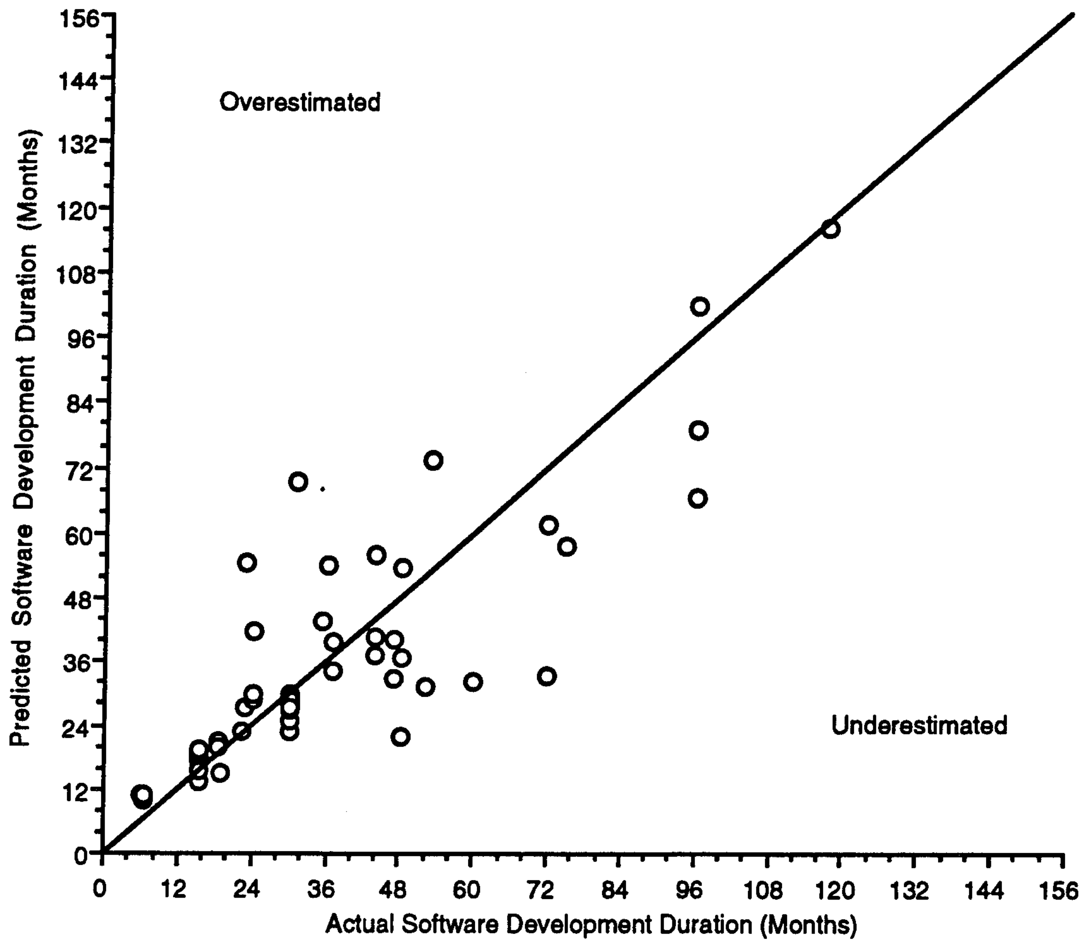


Figure IV-17. Equation 9.1 Predicted Versus Actual Software Duration

V. MODEL INTEGRATION AND APPLICATION

A. INTEGRATION

In Chapter IV, we present the results of our analyses of schedule intervals for the development and manufacturing of unmanned spacecraft systems. The task now is to fit those analyses together so that a consistent and useful assessment tool results. To do this, we must define how the intervals relate to one another. Development and production are linked through the first flight-model spacecraft. Delivery of the first flight-model spacecraft marks the end of development. System acceptance test completion for flight-model spacecraft is the milestone to which the manufacturing intervals are normalized. For most programs, acceptance test completion corresponds to delivery or is separated from delivery by one or two months.

In integrating the estimating relationships, we considered delivery and acceptance test completion as analogous. Once we estimate the first flight-model delivery using one of the development relationships, we can then estimate the manufacturing milestones for the first flight-model spacecraft. Given a specification of production quantities and the production rate build-up, we can estimate manufacturing milestones consistent with the production schedule. For example, if we specify a production program such that the delivery of the second spacecraft is to occur six months after first delivery, we can use the manufacturing time-estimating relationship to calculate when fabrication start, assembly start, system test start, and system assembly completion should occur. Doing this for the entire production program will give estimates of the level of manufacturing activity going on in the plant at any one time. Such information is important because production rates proposed for BMDO spacecraft programs such as Brilliant Pebbles are often much higher than for any previous spacecraft program. The analysis can also provide measures of development/production concurrency. For example, we can estimate the number of spacecraft in process before the start of acceptance testing for the first flight-model spacecraft.

The relationship between software CSCI development and the whole of the program schedule is not clear. Since each CSCI may be associated with a different aspect of system development or deployment/operations, it is difficult to specify what software development schedules must be in order to support a given development schedule. A complicating factor is that the estimating relationships do not cover the integration and test associated with merging the CSCIs into an integrated system. In order to exercise our software-estimating relationships, we made some simplifying assumptions, which are discussed in section B. Although the assumptions are unrealistic, they allowed us to demonstrate the application of the estimating relationships.

B. APPLICATION

There are two ways to approach the application of the estimating relationships presented in the previous chapter. The easiest approach is to use the model in its role as an assessment tool. Once the relevant intervals are identified in a proposed schedule, comparisons can be made with intervals estimated from the equations described in Chapter IV. The more difficult approach is to generate an estimated schedule where no proposed schedule exists. Although the first approach is more attuned to the goals of this research, the second approach will illuminate the important aspects of both types of applications. We took the latter approach to generate an example schedule for a hypothetical space system program. In the next subsection we estimate an overall development schedule; in the subsection following that, we analyze the software development schedule as it relates to the overall program schedule.

1. Overall Development Schedule

Before applying the estimating relationships for development and manufacturing, some assumptions must be made about the hypothetical program and the spacecraft associated with it. Our hypothetical spacecraft, the SDS-Ø, is a medium-sized operational sensor spacecraft developed for the Air Force. Its BOL power is rated at 600 watts. Its design life is 120 months. The spacecraft is being developed under a prototype approach where a qualification model is the first unit built and the first flight-model is the second unit built. The SDS-Ø is a proliferated system with a production run of 35 spacecraft (including the flight-model spacecraft built during development) delivered over 5 years with a peak delivery rate of 12 spacecraft per year. Deliveries are specified as follows:

- Year 1: two deliveries,
- Year 2: three deliveries,
- Year 3: seven deliveries,

- Year 4: twelve deliveries, and
- Year 5: ten deliveries.

We can choose from a variety of estimating relationships for estimating development program length. Given the specifications of the SDS-Ø and the data coverage associated with each of the estimating relationships, we chose equation 3.1, which is the augmented estimating relationship for operational spacecraft,

$$\text{1stDEL} = .510\ (\text{BOL Power})^{.537}\ (\text{DESLIF})^{.180}\ 1.588^{(\text{SENSOR})}\ 1.532^{(\text{NAV})}\ .756^{(\text{COMMER})}.$$

Substituting the appropriate values yields:

$$\text{1stDEL} = .510\ (600)^{.537}\ (120)^{.180}\ 1.588^{(1)}\ 1.532^{(0)}\ .756^{(0)} = 59.2.$$

We estimated the time from development start to CDR using equation 6.0,

$$\text{Months to CDR} = 1.809\ (\text{BOL Power})^{.311},$$

which yields

$$\text{Months to CDR} = 1.809\ (600)^{.311} = 13.3 \text{ months}.$$

For manufacturing time, we used equation 8.0,

$$\text{ManTime} = .747\ (\text{1stDel})\ (\text{CumQ})^{-.120}\ .274^{(\text{CAss})}\ .385^{(\text{STest})}\ .637^{(\text{SAss})}\ 1.515^{(\text{DELAY})},$$

where we included the estimate for 1stDEL from equation 3.1. Ignoring the DELAY variable, we calculated a set of manufacturing times for each of the 35 spacecraft in the hypothetical SDS-Ø program. Because the first flight-unit for the SDS-Ø program is the second unit built, the value of CumQ for the first flight-unit is two. By subtracting manufacturing times from the delivery dates (as normalized to months from development start) implied by the production schedule presented previously (where the first delivery date is calculated from the development TER), we calculated an overall acquisition schedule.

In order to implement the DELAY variable, we first calculated the probability of an occurrence of a manufacturing delay using our data sample. The data include information on 43 different spacecraft production units (here we excluded the first flight-unit for each program), and seven units are defined as experiencing a production delay. Thus, the probability of a delay indicated by the sample is .162. Appendix E presents an alternative method for calculating probabilities. Because the DELAY variable takes on either the value of 1 or 0, we can generate values for each of the 34 production units using random numbers drawn from a binomial distribution with a parameter value of .162. For those spacecraft units for which the value of 1 was drawn, we multiplied the manufacturing times by 1.515 and added them to the fabrication start milestone already estimated from the model. The resulting schedule is presented in Table V-1. Figure V-1 presents this schedule graphically. Spacecraft units for which the value of one was drawn include units 19, 24, 28, and 30.

Table V-1. SDS-Ø Acquisition Schedule

	Months from Development Start to:					
Spacecraft Number	CDR	Fabrication Start	Assembly Start	System Test Start	Assembly Completion	Delivery
1	13.3	18.5	33.3	43.6	48.1	59.2
2		26.5	40.6	50.3	54.6	65.2
3		33.8	47.4	56.8	61.0	71.2
4		39.8	53.0	62.2	66.3	76.2
5		44.6	57.5	66.5	70.5	80.2
6		48.2	61.0	69.8	73.7	83.2
7		51.8	64.3	73.0	76.8	86.2
8		54.3	66.6	75.2	79.0	88.2
9		56.7	68.9	77.3	81.1	90.2
10		59.1	71.1	79.5	83.2	92.2
11		60.4	72.4	80.6	84.3	93.2
12		61.7	73.6	81.7	85.4	94.2
13		63.0	74.7	82.8	86.4	95.2
14		64.3	75.9	83.9	87.5	96.2
15		65.5	77.1	85.0	88.6	97.2
16		66.8	78.2	86.1	89.6	98.2
17		68.0	79.3	87.2	90.7	99.2
18		69.2	80.5	88.3	91.8	100.2
19		70.4	87.4	99.1	104.4	117.1
20		71.6	82.7	90.4	93.9	102.2
21		72.7	83.8	91.5	94.9	103.2
22		73.9	84.9	92.6	95.9	104.2
23		75.0	86.0	93.6	97.0	105.2
24		76.2	92.7	104.2	109.3	121.7
25		77.3	88.2	95.7	99.1	107.2
26		78.5	89.3	96.8	100.1	108.2
27		79.6	90.4	97.8	101.1	109.2
28		80.7	97.0	108.2	113.2	125.5
29		81.8	92.5	99.9	103.2	111.2
30		83.0	99.1	110.3	115.2	127.3
31		84.1	94.7	102.0	105.3	113.2
32		85.2	95.7	103.1	106.3	114.2
33		86.3	96.8	104.1	107.3	115.2
34		87.4	97.9	105.1	108.4	116.2
35		88.5	98.9	106.2	109.4	117.2

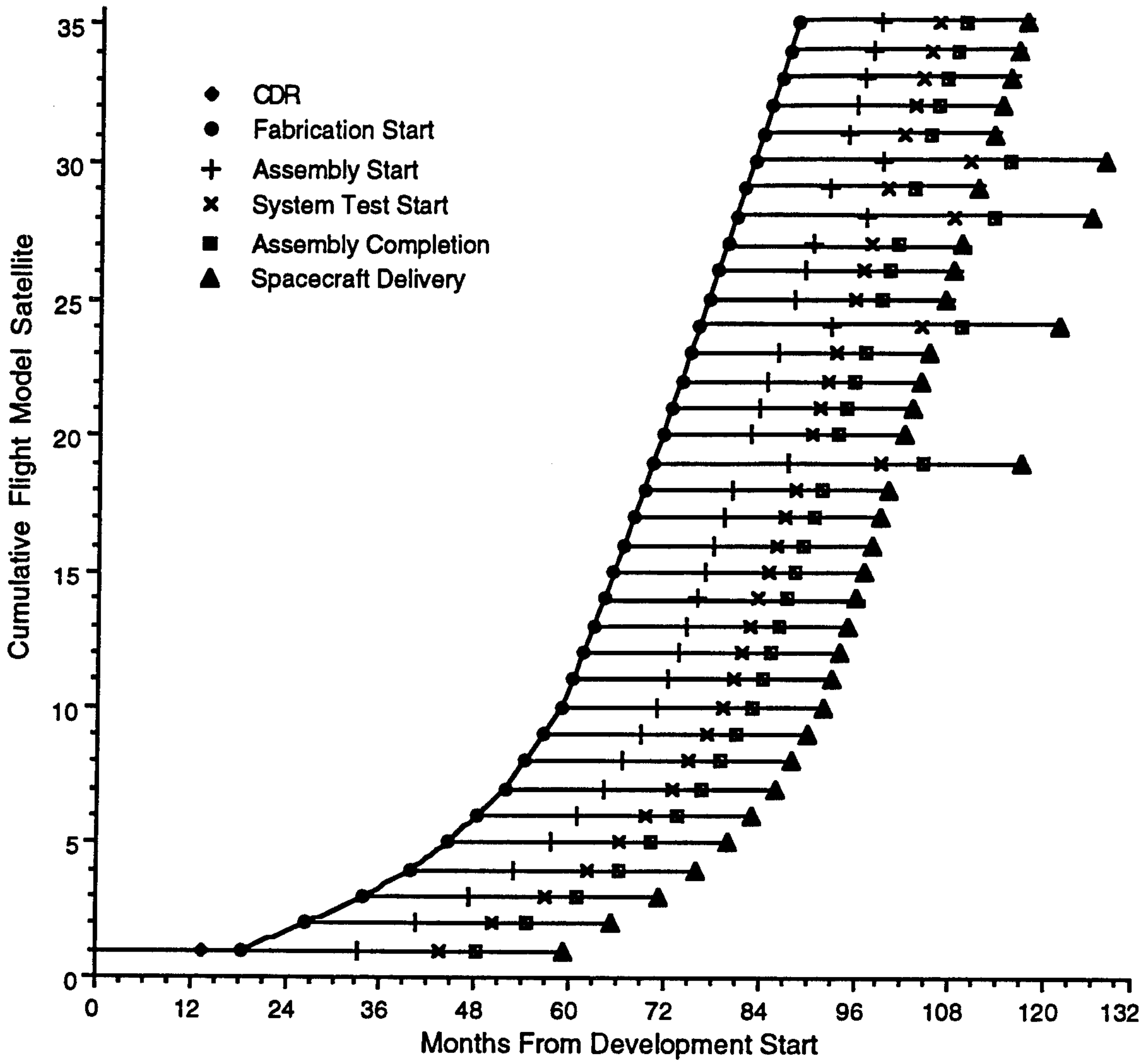


Figure V-1. SDS-Ø Program Schedule

The schedule for the first flight-model spacecraft is the development schedule. From the estimated schedule, analysts can calculate the number of spacecraft in process at a given time. From this number, requirements for tooling and test equipment needed to support the proposed delivery schedule can be inferred. Simulations of the delayed units can be used to gauge the impact of probable delays on the overall program schedule as well as tooling and test equipment requirements.

2. Software Development Schedule

For software, we assumed only two CSCIs, one for space-based software associated with the spacecraft and one for ground-based software associated with the system's ground-control segment. In order to apply the software-estimating relationship, we first made assumptions about when the software is required for the program to proceed on schedule. For the SDS-Ø program, we assumed that the space-based software begins preliminary design at the beginning of the development program and must be complete by the beginning of system test; this means a development duration of 43.6 months. For the ground-segment, we assumed preliminary design starts at spacecraft CDR and must be complete by the delivery of the fifth spacecraft; this translates into a development duration of 66.9 months. Software sizes are 500 KSLOC and 2000 KSLOC. The question is: What average staff level do we need to support the development schedule?

Starting with equation 9.1, we solved for average staff level, yielding

$$\text{Average Staff Level} = [(28.18\ (\text{KSLOC})^{.698}(.693)^{(\text{System})}(.254)^{(\text{Ground})})/\text{Duration}]^{(1/.613)}.$$

Solving for the space-based software, we get:

$$\text{Average Staff Level} = [(28.18\ (500)^{.698})/43.6]^{(1/.613)} = 286.9.$$

Solving for the ground-based software, we get:

$$\text{Average Staff Level} = [(28.18\ (2000)^{.698}\ (.254)^{(1)})/66.9]^{(1/.613)} = 299.6.$$

As we derived equation 9.1 using regression analysis, the calculated values indicate the staff level required for the statistical expectation of the development duration to be equal to the duration required by the assumptions of the example. Where the two development efforts overlap a combined average staff level of 586.5 software engineers is needed.

The data and analyses presented in this paper can be applied to schedule assessment problems in many more ways. The SDS-Ø example is not exhaustive; its main function is to provide examples so that BMDO analysts can make better use of the analyses provided.

APPENDIX A

PROGRAM SCHEDULES

Table A-1. Application Explorer Mission-Heat Capacity Mapping Mission (AEM-HCMM)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Dec 74	0
Production		
First Flight Article		
Acceptance Testing Complete	Aug 77	32
Production Deliveries		
Delivery 1 (First Flight Article)	Aug 77	32
Production Launches		
Launch 1	Apr 78	40

Table A-2. Atmospheric Explorer-C (AE-C)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Oct 71	0
Development PDR	Feb 72	4
Development CDR	Aug 72	10
Production		
Long Lead Materials Release	Apr 72	6
First Flight Article		
Component Fabriciation Start	Jul 72	9
Production Deliveries		
Delivery 1 (First Flight Article)	Dec 73	26
Production Launches		
Launch 1	Dec 73	26

Table A-3. Defense Meterological Satellite Program Block 5D-1 (DMSP 5D-1)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Mar 72	0
Development PDR	Jul 72	4
Development CDR	Mar 73	12
Qualification Model Testing		
Sys. Level Qual. Testing Start	Nov 73	20
Sys. Level Qual. Testing End	Aug 75	41
Production		
First Flight Article		
Acceptance Testing Start	Jun 74	27
Acceptance Testing Complete	Jun 76	51
Production Deliveries		
Delivery 1 (First Flight Article)	Jun 76	51
Delivery 2	Mar 77	60
Delivery 3	Oct 77	67
Delivery 4	Feb 78	71
Delivery 5	May 78	74
Production Launches		
Launch 1	Sep 76	54
Launch 2	Jun 77	63
Launch 3	May 78	74
Launch 4	Jun 79	87
Launch 5	Jul 80	100

Table A-4. Defense Meterological Satellite Program Block 5D-2 (DMSP 5D-2)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Apr 75	0
Development PDR	May 75	1
Development CDR	Nov 75	7
Qualification Model Testing		
Sys. Level Qual. Testing End	Nov 80	67
Incomplete Model Testing		
Thermal Model Testing	Apr 81	72
Production		
Long Lead Materials Release	Feb 75	-2
Production ATP	Jun 75	2
First Flight Article		
Acceptance Testing Start	Jul 79	51
Acceptance Testing Complete	Jan 82	81
Production Deliveries		
Delivery 1	Mar 82	83
Delivery 2	Jul 83	99
Delivery 3	Apr 85	120
Delivery 4	Dec 86	140
Delivery 5	Oct 87	150
Production Launches		
Launch 1	Dec 82	92
Launch 2	Nov 83	103
Launch 3	Jun 87	146
Launch 4	Feb 88	154
Follow-on Production ATP	Aug 83	100
Follow-on CDR	Apr 84	108
Follow-on Deliveries		
Delivery 1	Mar 84	107

Table A-5. Defense Satellite Communications System Phase II (DSCS II)

Milestones	Dates	Months from Development Start
Concept Exploration (CE)		
CE Contract	Oct 68	-5
Development		
Development Contract Award/ATP	Mar 69	0
Development PDR	Jul 69	4
Development CDR	Sep 70	18
Development FDR	Dec 70	21
Production		
Production Deliveries		
Delivery 1	Sep 71	30
Production Launches		
Launch 1	Nov 71	32
Launch 2	Dec 73	57
Launch 3	May 75	74
Launch 4	May 77	98
Launch 5	Mar 78	108
Follow-on Program	Oct 74	67
Follow-on Long Lead Release	Oct 74	67
Follow-on Launches		
Launch 1	Dec 77	105
Launch 2	May 78	110
Launch 3	Dec 78	117
Launch 4	Nov 79	128
Launch 5	Oct 82	163

Table A-6. Defense Satellite Communications System Phase III (DSCS III)

Milestones	Dates	Months from Development Start
Concept Exploration (CE)		
Milestone 0	Jun 73	-44
Milestone I	Dec 74	-26
CE Contract	Feb 76	-12
Development		
Milestone II	Dec 76	-2
Development Contract Award/ATP	Feb 77	0
Development PDR	Nov 76	-3
Development CDR	May 78	15
Development Testing Start	Feb 77	
Development Testing End	May 78	15
Qualification Model Testing		
Qual. Model Comp. Fab. Start	May 78	15
Qual. Model Comp. Fab. End	Jul 79	29
Qual. Model Comp. Testing Start	Nov 78	21
Qual. Model Comp. Testing End	Apr 80	38
Qual. Model Assembly Complete	Jun 80	40
Sys. Level Qual. Testing Start	Jul 80	41
Sys. Level Qual. Testing End	Feb 81	48
Incomplete Model Testing		
Thermal Model Testing	Sep 77	7
Development Model Testing	Oct 78	20
Structural Model Testing	Mar 80	37
Production		
Milestone III	Dec 81	58
Long Lead Materials Release	Dec 80	46
Production Readiness Review	Jun 81	52
Production Contract	Oct 82	68
Functional Configuration Audit	Mar 81	49
Physical Configuration Audit	Mar 81	49
First Flight Article		
Component Fabrication Start	Sep 78	19
Acceptance Testing Start	Jul 80	41
Acceptance Testing Complete	May 81	51
Production Deliveries		
Delivery 1	Jun 81	52
Delivery 2	Jul 82	65
Delivery 3	May 85	99
Delivery 4	Jun 85	100
Delivery 5	Oct 86	116
Delivery 6	Dec 86	118
Production Launches		
Launch 1	Oct 82	68
Launch 2	Oct 85	104
Launch 3	Oct 85	104
Follow-on Program	Aug 84	90

Table A-7. Defense Support Program 1-4 (DSP 1-4)

Milestones	Dates	Months from Development Start
Concept Exploration (CE)		
Milestone 0	Jan 64	-35
CE Contract	Apr 66	-8
Development		
Development Contract Award/ATP	Dec 66	0
Development PDR	Dec 67	12
Development CDR	Dec 68	24
Qualification Model Testing		
Qual. Model Comp. Fab. Start	Jan 69	25
Qual. Model Comp. Testing Start	Jun 69	30
Qual. Model Comp. Testing End	Nov 69	35
Qual. Model Assembly Complete	Jul 69	31
Sys. Level Qual. Testing Start	Jul 69	31
Sys. Level Qual. Testing End	Feb 70	38
Incomplete Model Testing		
Development Model Testing	Oct 69	34
Structural Model Testing	Sep 68	21
Production		
First Flight Article		
Acceptance Testing Start	Dec 69	36
Acceptance Testing Complete	Sep 70	45
Production Deliveries		
Delivery 1	Oct 70	46
Delivery 2	Feb 71	50
Delivery 3	Apr 71	52
Delivery 4	Jun 71	54

Table A-8. Defense Support Program 5R/6R (DSP 5R/6R)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Oct 78	0
Development SRR	Oct 77	-12
Development PDR	Mar 79	5
Development SDR	Apr 78	-6
Production		
Production Contract	Jun 89	6
First Flight Article		
Acceptance Testing Start	Nov 83	61
Acceptance Testing Complete	Oct 84	72
Production Deliveries		
Delivery 1	Nov 84	73
Delivery 2	Aug 85	82

Table A-9. Defense Support Program 14-17 (DSP 14-17)

Milestones	Dates	Months from Development Start
Concept Exploration (CE)		
Milestone I	Feb 80	-21
CE Contract	Sep 80	-14
Development		
Development Contract Award/ATP	Nov 81	0
Development PDR	May 82	6
Development SDR	Jan 82	2
Development CDR	May 83	18
Structural Model Testing	Feb 86	51
Production		
Long Lead Materials Release	Mar 82	4
Production Contract	Oct 83	23
Production ATP	Jun 83	19
Functional Configuration Audit	Aug 88	81
Physical Configuration Audit	Aug 88	81
First Flight Article		
Component Fabrication Start	Oct 82	11
Component Fabrication End	Feb 86	51
System Assembly Start	Apr 85	41
System Assembly Complete	Jul 87	68
Acceptance Testing Start	May 87	66
Acceptance Testing Complete	Aug 88	81
Production Deliveries		
Delivery 1	Dec 88	86
Delivery 2	Jun 90	103
Delivery 3	Aug 91	117

Table A-10. Fleet Satellite Communications System (FLTSATCOM)

Milestones	Dates	Months from Development Start
Demonstration and Validation		
Milestone I	Jul 70	-28
Development		
Milestone II	Sep 71	-14
Development Contract Award/ATP	Nov 72	0
Development PDR	Jul 73	8
Development SDR	Sep 73	10
Development CDR	Dec 74	25
Development Testing Start	Jun 73	7
Development Testing End	Jun 75	31
Qualification Model Testing		
Qual.Model Assembly Start	May 75	30
Qual. Model Assembly Complete	Sep 75	34
Sys. Level Qual. Testing Start	Apr 75	29
Sys. Level Qual. Testing End	May 77	54
Production		
Milestone IIIA	Jul 75	32
Milestone IIIB	Nov 76	48
Production RFP	Nov 74	24
Production Contract	Oct 75	35
Functional Configuration Audit	Jun 77	55
Physical Configuration Audit	Nov 77	60
First Flight Article		
Component Fabrication Start	Sep 75	34
System Assembly Start	Dec 76	49
System Assembly Complete	May 77	54
Acceptance Testing Start	Aug 76	45
Acceptance Testing Complete	Dec 77	61
Production Deliveries		
Delivery 1	Dec 77	61
Delivery 2	Mar 79	76
Delivery 3	Oct 79	83
Delivery 4	Sep 80	94
Delivery 5	Jun 81	103
Production Launches		
Launch 1	Feb 78	63
Launch 2	May 79	78
Launch 3	Jan 80	86
Launch 4	Oct 80	95
Launch 5	Aug 81	105
Follow-on Program		
Follow-on Long Lead Release	Jan 82	110
Follow-on Production ATP	Apr 83	125
Follow-on CDR	Nov 84	144
Follow-on Deliveries		
Delivery 1	Apr 86	161
Delivery 2	Sep 86	166
Follow-on Launches		
Launch 1	Dec 86	169
Launch 2	Mar 87	172

Table A-11. Global Positioning System Block I (GPS I)

Milestones	Dates	Months from Development Start
Demonstration and Validation		
Milestone I	Dec 73	-6
Development		
Development Contract Award/ATP	Jun 74	0
Development PDR	Feb 75	8
Development CDR	Jun 75	12
Qualification Testing Model		
Sys. Level Qual. Testing End	Sep 77	39
Production		
Production Contract	Jan 75	7
Acceptance Testing Start	May 77	35
Production Deliveries		
Delivery 1	Jan 78	43
Delivery 2	Mar 78	45
Delivery 3	Aug 78	50
Production Launches		
Launch 1	Feb 78	44
Launch 2	May 78	47
Launch 3	Oct 78	52
Launch 4	Dec 78	54
Launch 5	Feb 80	68

Table A-12. Global Positioning System Block II (GPS II)

Milestones	Dates	Months from Development Start
Development		
Milestone II	Aug 79	-18
Development Contract Award/ATP	Dec 80	0
Development PDR	Aug 81	8
Development SDR	Jan 81	1
Development CDR	Mar 82	15
Qualification Model Testing		
Qual. Model Comp. Fab. Start	Dec 80	0
Qual. Model Comp. Fab. End	Feb 84	38
Qual. Model Comp. Testing Start	Jun 81	6
Qual. Model Comp. Testing End	Sep 86	69
Qual. Model Assembly Complete	Nov 83	35
Sys. Level Qual. Testing Start	Nov 83	35
Sys. Level Qual. Testing End	Mar 86	63
Incomplete Model Testing		
Thermal Model Testing	May 82	17
Development Model Testing	Jul 83	31
Structural Model Testing	Feb 83	26
Production		
Long Lead Materials Release	Sep 82	21
Production RFP	Oct 81	10
Production Contract	May 83	29
Production ATP	May 83	29
Functional Configuration Audit	Dec 85	60
Physcial Configuration Audit	Oct 85	58
First Flight Article		
System Assembly Start	Sep 84	45
System Assembly Complete	Jan 86	61
Acceptance Testing Start	Jan 86	61
Acceptance Testing Complete	Apr 87	76
Production Deliveries		
Delivery 1	Apr 87	76
Delivery 2	Jul 87	79
Delivery 3	Dec 87	84
Delivery 4	Apr 88	88
Delivery 5	Jun 88	90
Delivery 6	Aug 89	104
Delivery 7	Dec 89	108
Production Launches		
Launch 1	Feb 89	98
Launch 2	Jun 89	102
Launch 3	Aug 89	104
Launch 4	Oct 89	106
Launch 5	Dec 89	108

Table A-13. High Energy Astronomy Obervatory (HEAO)

Milestones	Dates	Months from Development Start
Concept Exploration (CE)		
Milestone 0	Mar 69	-38
Demonstration and Validation		
D&V RFP	Feb 70	-27
D&V Contract	May 70	-24
Development		
Development Contract Award/ATP	May 72	0
Development PDR	Apr 75	35
Development CDR	Feb 76	45
Production		
Production Deliveries		
Delivery 1	Apr 77	59
Production Launches		
Launch 1	Aug 77	63

Table A-14. Hubble Space Telescope (HST)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Oct 77	0
Development PDR	May 79	19
Development CDR	Mar 82	53
Production		
Production Deliveries		
Delivery 1	Jul 86	105
Production Launches		
Launch 1	Apr 90	150

Table A-15. International Telecommunications Satellite System IV (ISAT IV)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Oct 68	0
Production		
Production Deliveries		
Delivery 1	Dec 70	26
Production Launches		
Launch 1	Jan 71	27
Launch 2	Dec 71	38
Launch 3	Jan 72	39
Launch 4	Jun 72	44
Lanuch 5	Aug 73	58

Table A-16. International Telecommunications Satellite System (ISAT IVA)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	May 73	0
Development PDR	Dec 73	7
Development CDR	Jul 74	14
Development Testing Start	Oct 73	5
Development Testing End	Oct 74	17
Qualification Model Testing		
Qual. Model Comp. Fab. Start	Jun 73	1
Qual. Model Comp. Fab. End	Apr 74	11
Qual. Model Comp. Testing Start	Oct 73	5
Qual. Model Comp. Teting End	Jun 74	13
Qual. Model Assembly Complete	Aug 74	15
Sys. Level Qual. Testing Start	Oct 73	5
Sys. Level Qual. Testing End	Oct 74	17
Incomplete Model Testing		
Thermal Model Testing	Mar 75	22
Development Model Testing	Sep 74	16
Structural Model Training	Dec 74	19
Production		
Long Lead Materials Release	May 73	
Production Contract	May 73	
Production Deliveries		
Delivery 1	Aug 75	27
Delivery 2	Dec 75	31
Delivery 3	Oct 76	41
Production Launches		
Launch 1	Sep 75	28
Launch 2	Jan 76	32
Launch 3	May 77	48
Launch 4	Sep 77	52
Launch 5	Jan 78	56
Follow-on Program	Dec 74	19
Follow-on Long Lead Release	Dec 74	19
Follow-on Deliveries		
Delivery 1	Feb 77	45
Delivery 2	Jul 77	50
Delivery 3	Jan 78	56
Follow-on Launches		
Launch 1	May 77	48
Launch 2	Sep 77	52
Launch 3	Mar 78	58

Table A-17. International Telecommunications Satellite System (ISAT V)

Milestones	Dates	Months from FSD Start
Development		
Development Contract Award/ATP	Sep 76	0
Production		
Production Deliveries		
Delivery 1	Oct 80	49
Production Launches		
Launch 1	Dec 80	51

Table A-18. Mariner 5

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Dec 65	0
Development CDR	Apr 66	4
Thermal Model Testing	Jun 66	6
Strctural Model Testing	Jul 66	7
Production		
First Flight Article		
Acceptance Testing Start	Jan 67	13
Acceptance Testing Complete	Apr 67	16
Production Deliveries		
Delivery 1	Apr 67	16
Production Launches		
Launch 1	Jun 67	18

Table A-19. Mariner 6

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Feb 66	0
Development PDR	Mar 67	13
Development CDR	Nov 67	21
Production		
Production Deliveries		
Delivery 1	Dec 68	34
Delivery 2	Jan 69	35
Production Launches		
Launch 1	Feb 69	36
Launch 2	Mar 69	37

Table A-20. Mariner 10

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Apr 71	0
Production		
First Flight Article		
Acceptance Testing Start	Jun 72	14
Acceptance Testing Complete	Apr 73	24
Production Deliveries		
Delivery 1	Aug 73	28
Production Launches		
Launch 1	Nov 73	31

Table A-21. The North Atlantic Treaty Organization Satellite System (NATO III)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Mar 73	0
Qualification Model Testing		
Sys. Level Qual. Testing End	Feb 76	35
Production		
Production Readiness Review	Mar 76	36
Physical Configuration Audit	Mar 76	36
First Flight Article		
System Assembly Start	Apr 75	25
System Assembly Complete	Sep 75	30
Acceptance Testing Complete	Feb 76	35
Production Deliveries		
Delivery 1	Mar 76	36
Delivery 2	Dec 76	45
Delivery 3	Sep 78	66
Production Launches		
Launch 1	Apr 76	37
Launch 2	Jan 77	46
Launch 3	Nov 78	68
Follow-on Program	Dec 80	93
Follow-on Long Lead Release	Jul 80	88
Follow-on Deliveries		
Delivery 1	Jul 84	136
Follow-on Launches		
Launch 1	Nov 84	140

Table A-22. Space Test Program Flight (P-72-2)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Jul 72	0
Development PDR	Oct 72	3
Development SDR	Jan 73	6
Development CDR	Apr 73	9
Development FDR	Jul 73	12
Development Testing Start	Jan 73	6
Development Testing End	Feb 74	19
Production		
First Flight Article		
Component Fabrication Start	Oct 72	3
Component Fabrication End	Jan 74	18
System Assembly Start	Jan 74	18
System Assembly Complete	May 74	22
Acceptance Testing Start	May 74	22
Acceptance Testing Complete	Mar 75	32
Production Deliveries		
Delivery 1	Mar 75	32
Production Launches		
Launch 1	Apr 75	33

Table A-23. Satellite Business Systems (SBS)

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Dec 77	0
Development PDR	Apr 78	4
Development CDR	Jan 79	13
Development FDR	Dec 79	24
Development Testing Start	Jan 78	1
Development Testing End	Jun 79	18
Qualification Model Testing		
Qual. Model Comp. Fab. Start	Apr 78	4
Qual. Model Comp. Fab. End	Jun 79	18
Qual. Model Comp. Testing Start	Aug 78	8
Qual. Model Comp. Testing End	Aug 79	20
Qual. Model Assembly Complete	Dec 79	24
Sys. Level Qual. Testing Start	Apr 79	16
Sys. Level Qual. Testing End	Jan 80	25
Incomplete Model Testing		
Thermal Model Testing	Jun 79	18
Structural Model Testing	Dec 78	12
Production		
Long Lead Material Release	Dec 77	0
Production Contract	Dec 77	0
Production Deliveries		
Delivery 1	Sep 80	33
Delivery 2	Jun 81	42
Delivery 3	Mar 82	51
Production Launches		
Launch 1	Nov 80	35
Launch 2	Sep 81	45
Launch 3	Nov 82	59
Follow-on Program	Nov 81	47
Follow-on Long Lead Release	Nov 81	47
Follow-on Deliveries		
Delivery 1	May 84	77
Follow-on Launches		
Launch 1	Aug 84	80

Table A-24. Spacecraft Charging at High Altitudes (SCATHA)

Milestones	Dates	Months from Development Start
Demonstration and Validation		
Milestone 1	Jun 75	-9
Development		
Development Contract Award/ATP	Mar 76	0
Development PDR	Jan 77	10
Development CDR	May 77	14
Production		
Production Deliveries		
Delivery 1	Oct 78	31
Production Launches		
Launch 1	Feb 79	35

Table A-25. Tracking and Data Relay Satellite System (TDRSS)

Milestones	Dates	Months from Development Start
Concept Exploration (CE)		
Milestone 0	May 71	-67
Demonstration and Validation		
Milestone 1	May 74	-31
D&V Contract	Jun 75	-18
Development		
Development Contract Award/ATP	Dec 76	0
Development PDR	Apr 77	4
Development SDR	Feb 77	2
Development CDR	Aug 78	20
Development FDR	Dec 79	36
Development Testing Start	Apr 77	4
Qualification Model Testing		
Qual. Model Comp. Testing Start	Jan 78	13
Qual. Model Comp. Testing End	Apr 82	64
Production		
First Flight Article		
Component Fabrication Start	Oct 77	10
Component Fabrication End	Aug 82	68
Acceptance Testing Start	Jun 79	30
Acceptance Testing Complete	Nov 82	71
Production Deliveries		
Delivery 1	Dec 82	72
Delivery 2	Dec 84	96
Delivery 3	May 88	137
Production Launches		
Launch 1	Apr 83	76
Launch 2	Jan 86	109
Launch 3	Sep 88	141
Launch 4	Mar 89	147
Launch 5	Jul 90	163

Table A-26. Viking Orbiter

Milestones	Dates	Months from Development Start
Development		
Development Contract Award/ATP	Feb 70	0
Development PDR	Oct 71	20
Development CDR	Jul 73	41
Development Testing Start	Jan 74	47
Qualification Model Testing		
Sys. Level Qual. Testing End	Sep 74	55
Production		
First Flight Article		
Acceptance Testing Start	Jan 74	47
Acceptance Testing Complete	Jan 75	59
Production Deliveries		
Delivery 1	Feb 75	60
Production Launches		
Launch 1	Aug 75	66
Launch 2	Sep 75	67

APPENDIX B

PROGRAM DESCRIPTIONS

APPENDIX B

PROGRAM DESCRIPTIONS

APPLICATION EXPLORER MISSION-HEAT CAPACITY MAPPING MISSION (AEM-HCMM)

The AEM-HCMM was designed to measure variations over the diurnal cycle in the Earth's surface temperature. The AEM-HCMM traveled in a near-polar sun-synchronous orbit, acquiring images in both the visible and infrared (IR) spectrums. The AEM-HCMM's primary instrument is an Earth-pointing heat capacity mapping radiometer (HCMR), which has a small geometric field of view, high radiometric accuracy, and a swath width of 700 kilometers. Data from the AEM-HCMM was used to estimate the Earth's capability to retain heat (thermal inertia) [B-1].

At a dry weight of 185 pounds, the AEM-HCMM is the lightest spacecraft in our data sample. The spacecraft is of modular design with two main components, the base module and the instrument module. The contractor for the base module was Boeing Aerospace Company. Boeing's module contains the data-handling equipment, power supply, communications equipment, and command and attitude control system. The prime contractor for the instrument module was International Telephone and Telegraph (ITT). The instrument module contains the HCMR and supporting equipment. The system integrator for the spacecraft was NASA's Goddard Space Flight Center (GSFC). GSFC's responsibilities included spacecraft design, integration and testing, and data processing [B-2].

Authority to proceed (ATP) for AEM-HCMM engineering development occurred in December 1974 [B-2]. The instrument module contract was awarded mid-1975 and the base module contract was awarded in November of the same year. Satellite integration and testing was completed in August 1977. This marks first delivery of the AEM-HCMM in our database. The AEM-HCMM was launched in April 1978 using a Scout-D launch vehicle [B-3].

ATMOSPHERIC EXPLORER-C (AE-C)

The AE-C was the first in a series of three satellites whose mission it was to examine energy transfer, atomic and molecular processes, and chemical reactions in the atmospheric regions from 60 to 100 nautical miles and above. The AE-C flew in an elliptical orbit of 2,321 by 83 nautical miles and had the ability to change its orbital perigee as much as 100 nautical miles. The AE-C was configured in the shape of a 16-sided polyhedron and houses 14 different scientific instruments, including spectrometers, photometers, and photo spectrometers [B-1]. At 170 watts maximum BOL power, the AE-C is the lowest-powered satellite in our database.

RCA's Astro Electronics Division was selected by NASA/GSFC as the AE-C's prime contractor in April 1971. Engineering effort did not begin until October 1971 with the award of NASA contract NAS 5-23003 to RCA. This is considered development start in our database. The original schedule called for delivery for launch in October 1973. Preliminary design review was accomplished in February 1972. During detail design, RCA sought to define spacecraft subsystems with sufficient engineering input so that configuration changes affecting subcontractors would be minimized and thus facilitate firm fixed-price subcontracting. Long-lead procurement activities began in April 1972, and system fabrication began in July 1972. Structural assembly began in the fall of 1972, and electrical integration tests began in the spring of that year. The spacecraft was delivered to GSFC for final integration tests in December 1973. This marks first delivery in our database. The AE-C was launched on a Delta rocket from the Western Test Range later that month [B-4].

DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP)

The DMSP satellites are designed to collect and transmit meteorological, oceanographic, and solar-geophysical data to support worldwide DoD operations. The procurement agency for the DMSP is the Air Force's Space Systems Division (SSD). The DMSP system is the only DoD meteorological satellite system. It consists of three-axis-stabilized satellites in 450-nautical mile, sun-synchronous polar orbits (98.7 degrees inclination). The primary sensor on the DMSP is the Operational Linescan System (OLS). The payload segment also contains several additional mission sensors. The OLS uses a telescope that scans the Earth's surface, moving back and forth along a 1,600-nautical mile swath and covering the entire globe in about 12 hours [B-5].

The DMSP program has used four generations of satellites, designated Block IV, 5A, 5B/C, and 5D. In general, each subsequent block was an enhancement of the previous block in the areas of spacecraft bus, greater redundancy in critical systems, larger sensor payloads, and greater autonomy. Block 5A was similar in design to Block IV but with a larger solar array and three-axis stabilization. Block 5B improved on Block 5A by including a still larger solar array and more sophisticated equipment and payload. Block 5D was broken into three sub-blocks. Block 5D-1 (units 1-5) has an 18-month design life; Block 5D-2 (units 6-10 and follow-on 11-14) has a 30-month design life and is known as an integrated spacecraft subsystem (meaning that much of the attitude determination and control subsystem and part of the telemetry and power subsystems are used during the ascent phase); and Block 5D-3 (units 15-20) has a 60 month mission life [B-5]. Block 5D-3 had yet to complete development during our data collection effort, so it is not included in our database. The space segment prime contractor for the overall DMSP program is RCA (later to be absorbed by General Electric). The prime contractor for the OLS, which is delivered to RCA as government-furnished equipment (GFE), is Westinghouse Electric Company (WEC) [B-6].

Block 5D-1

Block 5D-1 had three major upgrades over Block 5C: the functions of the spacecraft and the upper stage were combined in a single space vehicle resulting in weight savings; design life was increased from 9 to 18 months; the satellite's primary sensor, the OLS, was made more reliable; and the satellite was given the ability to carry a larger number of special sensors [B-6].

Block 5D-1 began development with a contract awarded to RCA in March 1972. The contract called for the delivery of four spacecraft (including a refurbished qualification unit) and was later modified to include one additional spacecraft. By the time of the preliminary design review (PDR), July 1972, the start and completion of integration and test (I&T) for all of the spacecraft had been delayed 3-4 months. At the time, delivery of the first satellite was to occur in February 1974. The critical design review (CDR) was held on March 1973. During 1973 significant effort was made to reduce the spacecraft weight. The first 5D-1 spacecraft was delivered in June 1976, 51 months after it entered development and 29 months later than its scheduled date at PDR. The second through the fifth satellites were delivered in March 1977, October 1977, February 1978, and May 1978. The considerable schedule slips in the DMSP 5D-1 program were due to problems with gyros in the attitude control system, new requirements to radiation-harden electronic equipment, changes to the reaction control subsystem, and problems with manufacturing [B-6].

The first Block 5D-1 satellite was launched on 11 September 1976. Spacecraft instability problems complicated by gyro failures required a recovery period. The spacecraft did not become operational until eight months after launch (June 1977). Six months after the first 5D-1 (F-1) became operational, a number of anomalies occurred. They included high bus voltage caused by solar array problems, failure of a tape recorder, transmitter power output drops, and degradation of the primary sensor. The second satellite (F-2) was launched in June 1977. In addition to its originally incorrect orbital inclination F-2 also suffered a number of technical problems such as gyros and main computer failures. This satellite was declared non-operational only a year and a half later (January 1980). The third satellite (F-3), launched in May 1978, had two major anomalies: failure of integrated circuits in the sensor in December 1979, and failure of the SSH special sensor failure in January 1980. By the end of 1980, the spacecraft was considered only partially operational. The fourth satellite (F-4) was launched in June 1979. After six months in orbit, the satellite started to suffer from battery cell failures, resulting in its computer shutdown and the loss of attitude control. F-4 was deemed non-operational in August 1980. The last Block 5D-1 (F-5) satellite was launched in July 1980 after a modification was made to correct deficiencies found during testing and reliability problems that had shown up in earlier satellites. F-5 failed to attain orbit due to the Thor launch vehicle's third stage malfunction and the resulting loss of all telemetry. This loss marked the end of the block 5D-1 series of the DMSP program [B-5 and B-6].

Block 5D-2

5D-2 changes involved the sensors as well as the spacecraft. Block 5D-2 is 18 inches longer and 320 pounds heavier than Block 5D-1. The improvements incorporated included: increased power subsystem output, larger memory on-board computers and more flexible and reliable subsystem telemetry. The 5D-2 used an upgraded primary sensor called the OLS-2, it was superior to the OLS-1 in having a programmable rather than a fixed processor, redundant rather than single-string electronics, and four rather than three tape recorders to improve its reliability and extend its lifetime. Also, new special sensors were added to the payload, an important mission sensor called the microwave imager (SSM/I) was added to the last two satellites of the series (F-9 and F-10).

Each satellite has two segments, spacecraft and payload. The spacecraft segment began to function during launch, when it monitored the ascent phase guidance of the booster. After booster separation, an apogee kick motor propelled the satellite to its final orbit, and as it did so, the spacecraft provided ascent guidance, electrical power, and telemetry. Once the satellite was in orbit, the spacecraft carried out the necessary housekeeping functions, including thermal control, attitude determination and control, generation and distribution of electrical power, communication with ground stations, processing of commands from ground stations, and monitoring and control of spacecraft equipment. All spacecraft activities, from launch through orbital operations, were controlled by on-board computers that were reprogrammable from the ground [B-6].

RCA was authorized to proceed with development and production of the DMSP block 5D-2 in April and June 1975. The original contract provided for the development and production of two flight units, F-6 and F-7. 5D-2 development followed a prototype approach where no qualification unit was procured and the first unit built was the flight unit. Concurrent with the F-6/F-7 development and production was the development and production of NASA's TIROS-N, a 5D-2 derivative. A second contract signed in September 1979 called for two follow-on spacecraft, the F-8 and F-9, with an option for an additional spacecraft, F-10. WEC was contracted to build four OLS-2 sensors [B-6 and B-7].

Major delays in the 5D-2 program were due to requirements changes and difficulties in testing. The 5D-2 was originally to be launched on an upgraded Thor booster (SLV-2A vs. LV-2F used to launch 5D-1), but weight growth required a still larger Atlas booster. Other major changes were brought about because of the life extension program (LEP), which resulted in the extension of the 5D-1's mean mission duration from 24 months to 36 months [B-8 and B-9].

Spacecraft system testing for F-6 began with the initial power turn-on (IPTO) test in July 1979. Testing was delayed from November 1979 until March 1980 because of LEP modifications to the spacecraft. At WEC, work proceeded slowly on the OLS-2 sensor because of additional improvements incorporated into the sensor design and problems experienced during testing. The first OLS-2 was delivered to RCA in July 1980. Modifications and retest associated with the change of launch vehicles caused a two-month delay in spacecraft system testing at the end of 1980. F-6 was finally delivered in March 1982 [B-10 and B-11].

F-6 was launched in December 1982, followed by F-7 in November 1983. Although both satellites experienced problems with hardware failures while in orbit (F-6 lost its SSH and SSIE mission sensors and gyros in the inertial measurement unit, and F-7 lost its B-side electronics in its OLS scanner drive motor and one of its gyros), they continued to operate and meet mission requirements through the end of FY 1985. The gyro problems were fixed by uplinking software to each spacecraft and restoring redundancy to the attitude control. F-6 exceeded its 30-month design life [B-6].

DEFENSE SATELLITE COMMUNICATIONS SYSTEM (DSCS)

The purpose of the DSCS is to provide secure worldwide communications for U.S. government agencies. The procurement agency for DSCS space segment hardware is Air Force SSD. The program can be broken into three distinct phases based on differences in space segment hardware. The Initial Defense Communications Systems Program (IDCSP) satellites made up the Phase I space segment of DSCS, which began operation in 1966. The IDCSP satellites were small, simple spacecraft that flew in low Earth orbit. Phase II (DSCS II) satellites were the follow-on to IDCSP. Although designed to be compatible with modified Phase I ground terminals, DSCS II satellites were totally different from the IDCSP satellites. DSCS II satellites were spin-stabilized and flew in geosynchronous orbit. Phase III satellites (DSCS III) offered still more communication capability in a still larger 3-axis stabilized bus with additional radiation hardening. Our data collection effort focused on DSCS II and DSCS III.

DSCS II

Built by TRW, the DSCS II weighs 1013 pounds dry. It provides a substantial increase in communications load and transmissions strength when compared with the IDCSP satellites. New features are a command subsystem, attitude control and station-keeping capability, multiple channels with multiple-access capability, and some measure of nuclear-hardening.

DSCS II began development in March 1969, achieved PDR in July 1969 and CDR in September 1970. The first satellite was delivered in September 1971 and the first launch occurred in November of that year. From 1971 through 1982, 15 DSCS II satellites were launched and positioned in geosynchronous orbits of 19,300 nautical miles. Four launch failures were due to anomalies related to the launch vehicle. The DSCS II satellites were launched by Titan IIIC in pairs, with the exception of DSCS II-16, which was launched with the first DSCS III using a Titan 34D/IUS [B-12].

DSCS III

The DSCS III constellation consists of five operational satellites and two on-orbit spares. Designed and built by General Electric, it has a design life of 10 years, is three-axis stabilized, and is nuclear-hardened. The satellites are equipped with six channels in the 7 to

8 GHz frequency band, which provide the flexibility to interface with various terminals. The on-board sensors instantly recognize jamming attempts. Computer and other elements are kept on the ground to save weight, space, and power on the satellite. The satellite can be launched by Titan IIIC, Titan 34D, Titan IV, Space Shuttle, or Atlas II. All DSCS III production satellites were scheduled for launch from the Space Shuttle before the Challenger accident. Currently, the plan is to use an expendable launch vehicle and consider the Space Shuttle for emergency use only [B-6].

DSCS III design studies and breadboards of certain components, especially the multiple-beam antenna, were done in 1976. PDR occurred in November 1976; the DSCS III was the only program in our sample where PDR occurred before the start of the engineering development contract. Engineering development started with a February 1977 contract for the design, development, and manufacture of a qualification model and two flight model satellites. The three satellites are known as A1, A2 and A3, where A3 was the qualification model refurbished for flight use under a supplemental contract [B-6].

There were two major reasons for the schedule variances that delayed the DSCS III's initial operational capability by approximately three years: cost overruns in development and delay of the qualification satellite testing. The cost overrun was due to parts and materials problems; and the delay in the qualification satellite testing was due to anomalies experienced with the subsystem-level automated test equipment and related software. There were also numerous late component deliveries and failures during the A1's system test, which extended the time required for its completion. A1 was finally delivered in June 1981 and was launched in October 1982 with a DSCS II. Eleven additional satellites were procured, B4 and B5, followed by B6 and B7 under separate yearly contracts and B8 through B14 through a multiyear contract. Additional delays in production and launching were incurred because Titan and Space Shuttle failures and the existence of still-functioning DSCS II satellites combined to give a lower priority to the DSCS III program [B-6].

DEFENSE SUPPORT PROGRAM (DSP)

The primary mission of the DSP is to help provide early warning of any ballistic missile raid against the U.S. or its allies. Other missions include detection of other booster launches and the detection of nuclear detonations in support of treaty verification. DSP satellites provided early warning of Iraqi SCUD missile launches during the Persian Gulf War. Common attributes of all DSP satellites include an infrared telescope primary sensor, a nuclear detonation sensor package, spin stabilization, and geosynchronous orbit. TRW and Aerojet were the integrating and sensor contractors for all generations of DSP satellites. The procurement agency for DSP space segment hardware is Air Force SSD.

DSP satellites, which comprise the space segment of the DSP system, can be categorized into as many as five generations. In our data collection effort we found that in terms of hardware differentiation and level of development effort it was most relevant to consider three different generations of DSP satellites. The original DSP satellite started development and production in 1966 with a four-satellite buy. In our database we refer to this design as DSP 1-4. Follow-on designs through satellite 13 had small evolutionary changes until the development of the DSP 5R/6R. The 5R and 6R satellites were fitted with a new IR sensor and nuclear detonation detection package. The 14th DSP satellite also marked a major upgrade with improvements in survivability, autonomy, and sensor resolution. In our database we refer to this design as DSP 14; in other sources, the design is often referred to as DSP-1 [B-13].

DSP 1-4

DSP 1-4 development started with the award of contracts to TRW and Aerojet in December 1966. The contract called for the development and production of four DSP satellites, one qualification model, and three flight models. CDR for both the spacecraft and sensor occurred in December 1968, 24 months after contract go-ahead. The first flight-model satellite was delivered in October 1970. Launch dates for DSP satellites are generally classified at the Secret level. Sensor development proved more problematic than development of the spacecraft bus; major cost overruns where incurred by Aerojet and the late delivery of the first flight sensor delayed the delivery of the first flight model spacecraft by four months. As a part of cost control measures it was decided to refurbish the qualification model satellite for use as a flight model (DSP 4) [B-14 and B-15].

Follow-on satellites to DSP 1-4 included evolutionary changes in various subsystems. Satellites 5-9 featured a design life extended from 18 months to 24 months; satellites 10-13 were designed with increased hardening along with a Molniya orbit capability for increased system survivability; design life was increased to 36 months [B-13].

DSP 5R/6R

DSP satellites 1-13 had in common the same basic IR sensor with a focal plane array of 2000 lead sulfide (PbS) detectors with capabilities restricted to the short-wave infrared waveband and below the horizon coverage. 5R and 6R were the first satellites to use the system evolutionary design (SED) sensor, which featured a 6,000-detector focal plane array, an experimental medium-wave infrared capability, above the horizon coverage, greatly increased processing capability and extended design life (60 months). The SED sensor was retrofitted to highly modified versions of satellites 5 and 6, which had been in storage; hence, the 5R and 6R designations. Changes to the spacecraft bus included increased power output, improved pointing accuracy, larger reaction wheels and survivability improvements [B-13 and B-16]. Dry weight of the DSP-5R/6R is 2,845 pounds compared with 1,074 pounds for DSP-1; beginning of life (BOL) power increased from 670 to 990 watts. The increased size of the satellite meant a change of launch vehicle from Titan IIIC to Titan 34D

DSP 5R/6R development started with a go-ahead for design work given TRW in October 1978. PDR was accomplished in March 1979. A letter contract was issued to TRW in June 1979. The contract covered design completion and production of satellites 5R and 6R. The first satellite delivery was to be in September 1982. Development of the SED sensor started well before the satellite; sensor PDR was accomplished in December 1976 with CDR in June 1978. Sensor development was complicated by a myriad of problems. Originally the focal plane detectors were to be of mercury cadmium telluride (HdCdTe). However, serious producibility problems resulted in changing back to PbS detectors. Other problems included difficulties in the signal electronics portions of the sensor [B-17]. Fabrication start for the SED sensor qualification article did not begin until the late 1979. Late delivery of components further delayed its fabrication and assembly. The qualification article was to be refurbished and installed in the 5R satellite. Some HdCdTe detectors were later incorporated into the 6R sensor as a part of the "two color" (medium-wave IR) experiment [B-9 and B-13].

Satellite 6R entered system testing during November 1983, before system testing began for 5R. Satellite 5R was put into storage shortly after system testing began in February 1984. Satellite 6R was delivered in November 1984; this marks the first delivery of the DSP-5R/6R in our database. 5R was later taken out of storage and modified; system testing began again in November 1984, and 5R was delivered in August 1985 [B-18 and B-19].

DSP 14

In terms of the satellite bus, the DSP 14 program represented the most extensive development within the DSP family. Survivability improvements were one of the main focuses of DSP 14 development. Upgrades were also made to the SED sensor; operational two-color capability was added [B-13]. The dry weight of the DSP satellite increased from 2,845 to 3,846 pounds and BOL power increased from 990 to 1,600 watts. The DSP 14 was the first of the DSP series to be Shuttle-compatible.

Development of the DSP 14 satellite began in November 1981. Separate contracts were let for design and development with the flight-model satellites, DSP 14-17, being procured under separate long-lead (March 1982 ATP) and production (June 1983 full funding) contracts. No dedicated qualification satellite was built as a part of DSP 14 development; DSP 14 was developed under a protoflight approach. The delivery of DSP 14 was originally planned for January 1987.

Originally, the Space Shuttle was to be the only launch vehicle to carry the DSP 14 satellites into orbit. In 1985, the Air Force directed TRW to design the spacecraft to be compatible with Titan IV boosters in addition to the shuttle. This redesign was originally to be effective with satellite 15. The decision proved auspicious in the wake of the 1986 Challenger accident; launch-vehicle-related delays for the DSP 14 were minimized [B-20].

DSP 14's PDR occurred in May 1982. Subsystem fabrication started with the structure subsystem in October 1982. CDR occurred in May 1983. All subsystems were to be delivered by March 1985. Deliveries of satellite subsystems were delayed because of the late delivery of components and piece parts, workmanship problems with some components, and problems with TRW test equipment. Particular problems were encountered with the mission data message (MDM) rebroadcast system, which was a totally new and very complex feature of the DSP 14 satellites. The MDM was not delivered until the summer of 1986. Problems and delays were also encountered in sensor testing [B-20, B-21, and B-22].

System assembly and testing of DSP 14 began in April 1985 and May 1987. Once started, system-level testing for the DSP 14 did not go smoothly. Again, the MDM caused many problems and delays. Acceptance testing was completed in August 1988, and the satellite was delivered in December 1988, a delay of 23 months from the original plan. Similar delays were evident in satellites 15 and 16 [B-23, B-24, and B-25]. A laser cross-link system was to be incorporated into satellites 15 and beyond; however, difficulties in development delayed its incorporation until satellite 17, which has yet to be delivered [B-25].

THE FLEET SATELLITE COMMUNICATIONS (FLTSATCOM) SYSTEM

FLTSATCOM provides tactical and strategic communications for the Navy (fleet broadcast and fleet relay), the Air Force (support for the bomber force and launch control centers, called the AFSATCOM system), and the Department of Defense (DoD). The satellites are follow-ons to TACSATCOM, Lincoln Experimental Satellite-6, and the leased channels of MARISAT (commercial). The constellation consists of four operational satellites in synchronous equatorial orbit plus an on-orbit spare. The Earth segment consists of shore-based ship, and aircraft terminals. Designed and manufactured by TRW, the FLTSATCOM weights 2,090 pounds dry, is three-axis stabilized, and has a design life of five years [B-6].

FLTSATCOM program experienced technical material and workmanship problems that involved several redesign efforts, delays in development test, qualification test, and production programs. The FLTSATCOM Research and Development Contract (F04701-73-C-011) was awarded to TRW on November 9, 1972, it called for the completion of the design phase in January 1974 and the qualification phase in June 1975. This contract provided for a Qualification Model Satellite, a Communication Simulator, a Spacecraft Command Program, and long lead-time production parts for the follow-on production effort. A change in launch vehicle (Titan IIIB/Agena to Atlas/Centaur), the need to eliminate single point failures, and vulnerability and hardening requirements all lead to extensive redesign of the spacecraft; hence, delaying the completion of the development test program by one year. Major problems arose with the UHF transmitter/receiver during the qualification model testing program. Correction of the problem required some redesign in each of the spacecraft's subsystems. The problem apparently caused a questioning of the feasibility of the entire program and, therefore, delayed construction of the first flight unit. Qualification testing was not completed until May 1977 [B-6 and B-26].

The first FLTSATCOM production contract was awarded to TRW in October 1975 with a planned completion date in January 1978, which was extended to September 1980. This contract called for the fabrication and testing of flights 1 (F1) and 2 (F2), and was later amended to include fabricating and testing a third spacecraft (F3) along with a spare set electronic boxes, and finally, launch support for F1, F2, and F3. The first satellite integration and test was delayed for almost 16 months due to late component delivery, engineering changes, acceptance testing duration increases, component failures, rework and integration, and other technical problems. Technical difficulties became evident after seven months of acceptance testing (April 1977-November 1977), several material and design deficiencies such as spurious outputs in the frequency generator and high in-rush current in the payload switching assembly. Along with acceptance tests, a mission readiness review was conducted by TRW from April to November 1977, an independent readiness review was conducted under SSD sponsorship between late August and mid-November, and a special readiness review was conducted by Lincoln Lab from July to early September. There were 76 action items, and 31 specific conclusions and recommendations to be done before the readiness activities were culminated on November 22, 1977. The first flight-model satellite was delivered to Cape Canaveral on December 3, 1977. It was launched in February 8, 1978, and placed in operation in April 1978 [B-6 and B-26].

Fabrication of the second flight model satellite began in early 1976, and assembly and test of components started in January 1977. Integration of the satellite was completed in November 1977, and acceptance testing began in January 1978. Due to the TRW factory fire in April 1978, FLTSATCOM (F2) experienced a schedule slip in integration and test of 13 months, it was not delivered until March 1979, and was launched on May 4. In October 1979, F3 was delivered but the launch did not occur until January 17, 1980. In October 1978, TRW was awarded another contract (F04701-78-C-90118) for the production of F4 and F5. F4 was launched on October 30, 1980. The last spacecraft in the original plan was launched in August 1981 but was damaged by a failure in the launch vehicle [B-6 and B-26].

The follow-on program production contract of three additional spacecraft (F6, F7, F8) was signed in April 1983. The follow-on spacecraft included the addition of an extremely high frequency (EHF) communication module, which increased spacecraft weight and power requirements. The deployment of the follow-on program commenced with the successful launch of the F7 spacecraft on December 4, 1986. The F6 spacecraft was destroyed in a lightening-related launch failure on March 26, 1987. The last of the three follow-on spacecraft, F8, was launched on September 25, 1989, after being delayed by a ground accident that severely damaged the Centaur. The five operational satellites will begin to drop out of service in 1997-2000 at the latest as onboard propellant is exhausted, but they will still far exceed their planned five-year lifetimes [B-6].

GLOBAL POSITIONING SYSTEM (GPS)

The space segment of the GPS consists of two distinct generations of satellites, Block I and Block II. The fully operational GPS constellation was originally to consist of 24 satellites orbiting the Earth at 10,900 nautical miles. The number was later reduced to 18. The navigation payload carried by each GPS satellite includes three or four atomic clocks and a Pseudo-Random Noise Signal Assembly (PRNSA). Information from the clocks and the PRNSA is combined in L-band signals, which carry coded timing pulses and data on the spacecraft's position. Signals from multiple satellites are processed by land-, air-, or sea-based receivers to produce accurate position, direction of travel, and velocity data for individual users. A fully operational 24-satellite constellation would provide three-dimensional worldwide (98% with 18 satellites) coverage [B-22].

The GPS program is a joint service effort and the Air Force SSD is the acquisition agency for the space segment. The program is one of the few in our database that followed the standard DoD acquisition schedule with demonstration and validation (D&V), full-scale development (FSD), and production phases. The D&V phase began in December 1973 and consisted of the design, development, and manufacturing of one experimental satellite and five prototype operational satellites. The experimental satellite was built by the Naval research lab and was designated NTS-1. Rockwell International (Seal Beach) was the prime contractor for the design, development, and production of the prototype operational satellites and all following GPS satellites through the 40th unit. The prototype operational satellites were originally known by the NDS designation. Later they were identified as Block I Navstar GPS satellites. The original constellation of Block I satellites would support initial testing over a limited geographical area, the evaluation of prototype user equipment, and Trident missile development; they would later join the operational constellation. FSD began in August 1979. Additional Block I replenishment satellites were procured during FSD. In all, eleven Block I satellites were built (GPS 1-11). Block II development began during FSD with a contract for design, development, and a qualification article (GPS 12). The production phase involved the procurement of 28 Block II flight model satellites (GPS 13-40) [B-6]. Follow-on satellites are being procured from General Electric.

GPS Block I (GPS I)

GPS Block I satellites began development in June 1974 with a contract to Rockwell to design, develop, and build one qualification model and three flight-model satellites. First launch was scheduled for March 1977. An additional two satellites were added to the buy in 1976, bringing the total to six. The qualification model was later refurbished and became flight model GPS 6. GPS 1 through 3 would carry three rubidium clocks. Starting with GPS 4, a cesium clock would be added [B-17]. GPS 6 and beyond carry a nuclear-explosion detection sensor. Two additional replenishment lots of Block I satellites were procured (GPS 7–8 and 9–11).

PDR, originally scheduled to occur in October 1974, was delayed until February 1975. CDR occurred in June 1975. System testing on the qualification model was to be complete in June 1977. The unavailability of test equipment and hardware problems revealed by thermal-vacuum testing delayed completion until September. The qualification vehicle was then shipped to Vandenburg AFB for the testing of its compatibility with Air Force ground stations. The first flight-model satellite began system testing in May 1977. Difficulties with the solar array drive resulted in the cannibalization of the qualification vehicle to expedite the flight model's delivery. GPS-1 was delivered in January 1978 and was launched from Vandendurg AFB in February aboard an Atlas booster. This represented an 11-month stretch beyond the originally planned launch date of March 1977. GPS 1 became operational in March 1978. Satellites 2-4 were delivered and launched with only minor additional delays. The delays were due primarily to problems with the rubidium clocks.

GPS Block II (GPS II)

The GPS Block II design includes features to enhance the operational capabilities of the GPS system. Upgraded capabilities include a variety of survivability features, an increase in design life from 60 to 90 months, more accurate navigation signals and increased automation. The added capabilities were incorporated into an essentially new spacecraft bus; dry weight increased from 875 to 1,332 pounds and BOL power increased from 523 to 980 watts. The larger spacecraft required a change in launch vehicle from the Atlas F to the Space Shuttle [B-20].

GPS Block II development began in December 1980 with a contract awarded to Rockwell International to design, develop, and test the Block II qualification test vehicle (QTV) GPS 12. The system design review (SDR) for the Block II development and qualification satellite was held in January 1981. PDR occurred in August 1981. The Block II configuration development test vehicle (DTV) was built with mass simulators installed and subjected to acoustic testing beginning September 1981 to confirm the structural design and component vibro-acoustic environment before fabrication of the QTV. CDR was held March 20, 1982 [B-6].

In May 1983, the Air Force awarded Rockwell a multi-year production contract covering 28 Block II satellites GPS 13 through GPS 40. Long-lead items were authorized in September 1982. GPS 13 was the first Block II flight-model satellite. Because of the relatively high volume of output associated with the contract, Rockwell redesigned its Seal Beach production and test facilities in order to maximize efficiency and ensure that production rates could be met [B-21 and B-27].

System-level testing of the GPS-12 qualification satellite began in November 1983. Testing was suspended until October 1984 because of problems in the satellite's electronic boxes. Additional delays were incurred because of noise in the navigation system and spurious thruster firings. Thermal vacuum testing, which was performed at the Air Force's Arnold Engineering Development Center (AEDC), was delayed because of difficulties with test facilities. Six electronic boxes had malfunctioned during testing at AEDC causing further delays. As of October 1985, the Block II qualification program was already 15 months behind schedule and had incurred considerable cost growth. After reworking the affected electronic boxes qualification testing proceeded smoothly and qualification was achieved in March 1986 [B-21 and B-28].

System assembly of GPS 13 began in September 1984. From this point on the build-up of the spacecraft was on schedule until the installation of the electronic boxes. Workmanship problems delayed delivery of some of the boxes. Eventually, Rockwell decided to install non-flight boxes as place-holders so that assembly and integration could proceed. The last of the flight boxes were not delivered until December 1985; system-level testing began in January 1986. Two digital electronics and two radio frequency boxes malfunctioned during the first system test; the boxes were returned to their suppliers and testing was suspended until June. The completion of the final factory functional test was scheduled for January 1987. Further problems with electronic boxes delayed test completion until April. The Air Force took delivery of GPS 13 on April 27, 1987. Because of the unavailability of launch resources due to the Challenger accident of January 1986, GPS 13 was put into storage. Prior to storage the satellite underwent control segment compatibility testing at Cape Canaveral [B-22].

In order to minimize the schedule delay due to the stand-down of the Space Shuttle, a competition for an alternative medium-launch vehicle was initiated by the Air Force. McDonnell Douglas Delta II was selected as the alternative vehicle in January 1987. Rockwell was asked to conduct integration activities associated with the change in launch vehicles. Even with an alternative launch vehicle, considerable launch delays were still anticipated. In order to minimize storage and retest costs, the Air Force decided to extend the original GPS production schedule by three years. A modification incorporating the stretch was added to the production contract in May 1988. It appears from examining GPS program schedules that the first satellite affected by the schedule stretch was GPS-20; therefore, in the database, we treat satellites 13-19 as a distinct production block. GPS-15 is not included in the block because it was damaged in a factory fire and was not delivered until long after GPS 19. Difficulties in system testing with GPS 18 resulted in it being delivered after GPS 19. First launch for a GPS II satellite occurred with the launch of GPS 14 in February 1989; difficulties with GPS 13 at the launch site resulted in the substitution of GPS 14 [B-5].

HIGH ENERGY ASTRONOMY OBSERVATORY (HEAO)

The HEAO program consisted of three Earth-orbiting platforms that were equipped to collect high-quality, high-resolution data on X-ray, gamma-ray, and cosmic-ray sources. The first satellite in the series, HEAO1, was launched in August 1977, and the last, HEAO3, was launched in September 1979 [B-29].

The HEAO program was initiated in the spring of 1969 when Marshall Space Flight Center began its preliminary definition (phase A) study. In February 1970, an RFP was issued for a preliminary design study. In May 1970, Grumman and TRW were selected for the phase B study contracts which were completed 11 months later. In July 1971, a request for proposals (RFP) for development, manufacture, and testing of two HEAO satellites was issued. Full-scale development began in May 1972 [B-2], when TRW was awarded a contract to develop two HEAO satellites with an expected launch on a Titan III-E in 1975. Due to budget cuts in January 1973, the HEAO program was suspended for one year in order to restructure the program to cut costs. In April 1974, TRW was selected to be prime contractor for the redefined HEAO program, but contract negotiation was not completed until August 1974 [B-29]. The development PDR was held in April 1975, and CDR occurred in February 1976. The first HEAO was delivered in April 1977 and was successfully launched in August 1977 [B-2].

THE HUBBLE SPACE TELESCOPE (HST)

The HST, named after an American astronomer Edwin P. Hubble, was designed as the first long-term, maintainable, and repairable space observatory. It flies in low Earth orbit just above the atmospheric veil surrounding the Earth. The overall spacecraft is 42.5 feet long and weights 25,500 pounds. On the outside are four antennas for communications, two solar array panels that collect energy for the HST, and storage bays for electronic gear. There are three major elements of the HST: the Optical Telescope Assembly (OTA), the five Scientific Instruments (SIs), and a Support System Module (SSM) that contains all the structures, electronics, and power subsystems to operate the spacecraft [B-30].

The HST is dependent on the Space Shuttle for launch and deployment. The Shuttle provides the capability for scheduled on-orbit maintenance and reboost, and, if required, it can retrieve the HST and return it to Earth for refurbishment. The Tracking and Data Relay Satellite System (TDRSS) is used to transmit HST scientific and engineering data to Earth. With an expected operating life of at least fifteen years, the HST is the first major astronomical spacecraft designed for long-duration use. Early in the design phase, some of the major components identified as needing the most frequent maintenance, including most of the equipment in the SSM equipment section, were designed as modular orbital replacement units (ORU). These units are self-contained boxes mounted in equipment bays, and can be removed through doors or removable panels. Among the equipment so designed are the solar arrays, the batteries, the computers, the five instruments, the low-gain antenna, the reaction wheel assembly, and electronic and mechanical control units [B-29].

The HST, a joint effort by NASA and the European Space Agency, entered development in October 1977. Lockheed Missile & Space Company and Perkin-Elmer Corporation were the joint prime contractors. Lockheed built or supervised subcontract development of the equipment and the entire SSM, then assembled and test-verified the completed telescope. Perkin-Elmer designed and built the OTA, including the telescope's primary and secondary mirrors, the fine guidance sensors, and other optical subsystems. Marshall Space Flight Center was responsible for directing the building of the spacecraft, for proper integration of all its components, and for planning for on-orbit maintenance of the HST and such maintenance during its first year in operation. A group of international astronomers led development teams that created the five scientific instruments; Goddard Space Flight Center was responsible for the development and in-flight testing of the instruments. The HST program's PDR was held in May 1979, and CDR occurred in March 1982 [B-2].

At the time of the initial funding in 1978, the HST was scheduled to be launched in December 1983. In late 1982, the program had serious technical and managerial problems due to increases in the cost, size, and complexity of the program. Consequently, the launch date was rescheduled to the first half 1985. Unanticipated technical problems with some of the HST components resulted in another launch delay to October 1986. The Challenger accident in January 1986 again delayed the launch to June 1989 and finally to December 1989. Thermal vacuum verification testing was completed in July 1986. This marks first delivery in our database; we use this date as an approximation of the HST's final delivery if the Challenger accident had not occurred. The Challenger accident allowed time for a number of modifications to made to the HST. Some modifications were specified as a result of observations made during verification testing. The solar arrays were upgraded with new blankets incorporating back surface field reflectors and protection against atomic oxygen erosion. Features were also added to facilitate array replacement five years after initial deployment. The developer of the solar arrays, British Aerospace, received a contract in March 1988 to fabricate a second set of solar arrays for this replacement [B-29]. The HST was finally launched in April 1990 [B-2, B-30, and B-31].

INTERNATIONAL TELECOMMUNICATIONS SATELLITE SYSTEM (INTELSAT)

INTELSAT, a financial cooperative consortium consisting of 108 nations, owns, manages, and operates the world's largest commercial global communication satellite system. Currently, about two-thirds of the world's transoceanic communications travel via INTELSAT satellites, which are maintained in geostationary orbits, 19,300 nautical miles above the equator. INTELSAT is currently procuring its seventh generation of communication satellites. The separate systems are: ISAT I (Early Bird), ISAT II, ISAT III, ISAT IV and IVA, ISAT V and VA, ISAT VI, and ISAT VII. The ISAT IVA and VA designations refer to follow-on buys of spacecraft in which the communication capability differed significantly from that of the spacecraft procured in the original contracts. The satellites in use by INTELSAT at any one time represent several generations of satellite technology (e.g. in 1983, the Atlantic Ocean configuration consisted of an ISAT IVA and two ISAT Vs) [B-32].

ISAT IV

ISAT IV is the fourth generation of the commercial communications satellites developed and managed by INTELSAT. In October 1968, INTELSAT contracted with the Hughes Aircraft Company for development and production of four ISAT IV satellites. In July 1970, INTELSAT ordered four more satellites. The ISAT IV provided a large increase in capacity when compared to ISAT III: ISAT IV has an average of 3,750 simultaneous telephone circuits and two television channels compared to 1,500 and no television channels for ISAT III. Each satellite had one spot beam parabolic reflector and four global horns (two for transmitting and two for receiving). The spot beam antenna was steerable on commands from the ground and could transmit high-energy beams toward small areas on the Earth. ISAT IV was the first satellite to have narrow-beam antennas. It had multiple access and simultaneous transmission capabilities and added capability for digital communications. Design life was increased from five to seven years. The ISAT IVs were spin-stabilized in geosynchronous orbit, and had body-mounted solar cells to supply spacecraft power. Its antennas and communications electronics were mounted on a platform that is despun relative to the main body of the satellite in order to remain pointed at the Earth [B-32 and B-33].

The first ISAT IV was delivered in December 1970, 26 months from FSD start, and the first launch occurred one month later aboard an Atlas/Centaur launch vehicle. All eight ISAT IV satellites have been launched, with only one unsuccessful launch. The last launch was in May 1975, and some continued in active service until 1981. All ISAT IVs are now spare satellites, and the newer ISAT IVAs and ISAT Vs have assumed the active roles [B-33].

ISAT IVA

The ISAT IVAs were derivations on the ISAT IV models: the satellite bus and much of the communications subsystem remained unchanged, but alterations in the antennas and in the number of transponders allowed the communications capacity to increase to 6,000 circuits [B-32]. In addition to more efficient solar cells, the ISAT IVAs had five communication antennas: global coverage receiving, global coverage transmitting, spot beam receiving, and two spot beam transmitting. The new antennas and communications electronics allow an increase to twenty 36-MHz channels from the twelve on ISAT IV.

The development contract was signed with Hughes in May 1973. A PDR was held in December 1973, seven months after development start. CDR occurred in July 1974. Initially, three ISAT IVA satellites were ordered, followed by a second order for three more, in 1974 [B-33]. The first ISAT IVA was delivered in August 1975, three months later than originally planned. First launch was in September 1975, one month behind schedule. All six ISAT IVA satellites were launched between September 1975 and March 1978, but the fourth was lost as the result of a launch vehicle failure [B-33 and B-34].

ISAT V

The ISAT V is the first INTELSAT satellite to use three-axis stabilization. The main structure is in the form of a box upon which is mounted an antenna tower and from which extend "wings" of solar cells. It was the first satellite to employ 14/11 GHz as well as 6/4 GHz communications. The ISAT V's capacity doubled that of the ISAT IVAs—to 12,000 simultaneous telephone circuits plus two television channels. Design life remained at seven years. The ISAT Vs took 49 months to develop versus the ISAT IV's development time of only 26 months.

The ISAT V program began in September 1976 when INTELSAT contracted with the Ford Aerospace and Communications Corporation for development and production of seven satellites. The last three satellites were modified to add a maritime communications package following INTELSAT's order in June 1979. An additional satellite was ordered in April 1980, and again in January 1981 by INTELSAT. Three additional satellites of the ISAT V series were ordered in June 1981, and again in May 1982, bringing the total ordered to 15. The first ISAT V was delivered in October 1980 and launched in December 1980 by an Enhanced Atlas/Centaur. ISAT V can also be launched by Ariane-2 and the Space Shuttle [B-32].

MARINER

Our database contains three of the ten Mariner spacecraft that constituted NASA's Mariner planetary exploration program. These include Mariner 5, Mariner 6 and Mariner 10. The Mariner program was managed by NASA Headquarters' Office of Lunar and Planetary Exploration with the cognizant NASA center being the Jet Propulsion Laboratory (JPL). JPL acted as the prime contractor for all Mariner spacecraft except for Mariner 10 where Boeing was the prime. Mariner spacecraft 1–7 were designed for relatively short "flyby" missions of Mars (1–4, 6–7) or Venus (5), while spacecraft 8–9 were Mars orbiters and spacecraft 10's mission was a flyby of both Venus and Mercury. One characteristic of the Mariner series of spacecraft was a desire to retain as much design inheritance between missions as possible [B-29].

Mariner 5

The Mariner 5 was the spacecraft used for the Mariner-Venus 1967 mission. Mariner 5's mission was to fly within 3,200 kilometers of Venus to collect data on the planet's atmosphere, radiation, and magnetic fields. Instruments flown on the spacecraft included a helium magnetometer, plasma probe, trapped radiation detector and ultraviolet magnetometer. The launch vehicle for Mariner 5 was the Atlas SLV-3 with an Agena upper stage [B-35].

Project go-ahead occurred in December 1965; this marks the beginning of Mariner 5 development in our database. Development included a thermal control test model, a structural test model, a flight support spacecraft (67-1) and a flight model spacecraft (67-2). The flight support spacecraft is analogous to a qualification model. CDR occurred in April 1966. The flight support vehicle was delivered to JPL's spacecraft assembly facility (SAF) in October 1966. The flight vehicle was delivered to the SAF in December 1966; system testing began in January 1967. System testing was completed in April 1967 and the spacecraft was shipped to the Eastern Test Range (ETR) later that month; this marks first flight model delivery in our database. The spacecraft was launched in June 1967 and encountered Venus in October 1967. The mission was complete in December [B-36].

Mariner 6

The Mariner 6, along with Mariner 7, were the spacecraft used for the Mariner-Mars 1969 mission. Mariner 6's mission was to fly within 3,200 kilometers of Mars to collect data on the planet's atmosphere and surface in order to establish a basis for future experiments in search of life on Mars. Instruments flown on the spacecraft included a television camera, infrared radiometer, infrared spectrometer and an ultraviolet spectrometer. Mariner 6 was a considerably larger and more complex spacecraft compared to Mariner 5; dry weight was 909 pounds compared to 515 pounds and BOL power at Earth was 830 watts compared with 430 watts. The launch vehicle for Mariner 6 was the Atlas SLV-3 with a Centaur upper stage [B-35].

Program go-ahead was given by NASA headquarters in February 1966. In all, four spacecraft were built in support of the Mariner-Mars 1969 mission; a proof-test model (PTM), which was equivalent to a qualification model; two flight models, Mariner 6 and Mariner 7, and an assembled set of spares. Scientific payload selection was announced in May 1966. Budget cuts forced the scaling back of certain aspects of the project and the delay in delivery of some parts and components. The last of the subsystem PDRs were complete in March 1967, and the last of the CDRs were complete in November 1967. Mariner 6's structure was delivered by a subcontractor to JPL in December 1967. The completed Mariner 6 spacecraft was delivered to Kennedy Space Center in December 1968, and Mariner 7 was delivered in January 1969. Mariner 6 was launched at the end of February after a week's delay caused by the structural failure of the Atlas launch vehicle. Mariner 7 was launched a month later [B-35].

Mariner 10

The Mariner 10 was the spacecraft used for the Mariner Venus-Mercury 1973 mission. Mariner 10's mission was to fly by Venus and continue on to encounter Mercury, collecting data on both planets' atmospheres, environments, and body characteristics as well as the characteristics of the interplanetary medium. The Mariner 10 was the first spacecraft used for a dual-planet mission and the first to use the gravitational attraction of one planet to assist it in reaching another. Instruments flown on the spacecraft included a magnetometer, plasma science experiment, an infrared radiometer, ultraviolet spectrometer, a charged particle telescope, and a television system. The launch vehicle for Mariner 10 was the Atlas SLV-3 with a Centaur upper stage [B-35 and B-37].

The Mariner Venus-Mercury 1973 mission was unusual as JPL's concept for the mission had to compete with a concept from Goddard Space Flight Center (GSFC). JPL agreed to a not-to-exceed price of $98 million for the Mariner 10 project. A low-cost approach was taken for Mariner 10: all instruments were previously flight-qualified and a maximum amount of design inheritance (and even residual hardware) from previous Mariner missions was sought [B-37].

Mariner 10 was the only Mariner spacecraft to have a commercial prime contractor. An RFP was issued by JPL in December 1970 and the development contract was awarded to Boeing in April 1971. The contract called for the fabrication, assembly and test of one ground-test (qualification) spacecraft, one flight spacecraft and associated models, test and support equipment. When compared with earlier Mariner programs, Mariner 10 was distinguished by a relatively short design phase; subsystem and system design reviews were complete by the end of 1971. The spacecraft was delivered to ETR in August 1973 and launched from there in November [B-35 and B-37].

NORTH ATLANTIC TREATY ORGANIZATION (NATO) SATELLITE SYSTEM

The NATO satellite communications system was developed to handle diplomatic and military communications between the U.S. and the 13 other NATO countries. The program consisted of four phases. The first phase, which began in 1967, was the experimental use of the Initial Defense Communications Satellite Program (IDCSP) satellites with two ground terminals. The second phase, NATO II, began in 1968. Following an agreement between NATO and DoD, the Air Force began procurement of a two-satellite system for the NATO alliance [B-38]. The third phase, NATO III, began in 1973. Four NATO III satellites were bought, NATO IIIA, B, C, and D. Funded entirely by NATO, the program is managed by Air Force SSD on behalf of the NATO Communications and Information Systems Agency in Brussels. The two NATO II satellites, with an in-orbit weight of 129 kilograms, were launched by Delta on March 20, 1970 and February 2, 1971 [B-39]. In this report, we focus on NATO III.

NATO III is a spin-stabilized satellite with cylindrical body and a despun antenna platform on one end. All equipment is mounted within the body, and a three-channel (50, 17, and 85 MHz) rotary joint connects the communications subsystem with the antennas [B-33]. The NATO III spacecraft is about 7 feet in diameter and 10 feet long, including antennas, its weight is 1,543 pounds at launch, 829 pounds in final geosynchronous orbit, and 771 pounds dry. Electrical power during sunlit portions of the orbit is provided by solar cells mounted on the periphery of the spinning cylinder. The communications subsystem consists of two continuous transmitters, one each for European and Atlantic coverage. The NATO IIIA was in geosynchronous orbit 19,300 nautical miles above the

Atlantic Ocean. It has a design life of 7 years, and is interoperable with DSCS [B-40, B-41, and B-42].

The NATO III prime contractor is Ford Aerospace; Marconi Space and Defense Systems in the United Kingdom provided components for the communications and attitude control subsystems. Prime contractor for the Delta 2914 launch vehicle and launch service is McDonnell Douglas Astronautics Corporation [B-43]. In March 1973, a contract of $27.7 million was awarded to Ford Aerospace to design and build three NATO III satellites, A, B, and C. NATO IIID was bought under a 1980 contract and incorporated numerous upgrades [B-33]. NATO IIIC was originally the qualification unit and was later refurbished into a flight model. The original plan called for the first flight satellite's acceptance testing to be complete by July 1975. Acceptance testing was completed in February 1976, a total delay of eight months from the original schedule. Shortly before that, the launch date was delayed an additional two months to April 1976. This schedule delay was due to several technical problems experienced during spacecraft thermal-vacuum testing in early December 1975. Schedule delays before that were primarily due to delays in parts procurement [B-43]. The NATO IIIA was delivered March 5, 1976. The spacecraft underwent validation (functional) testing at the launch site from 14 March to 30 March; all subsystems checked out satisfactorily except for one component, the traveling-wave-tube amplifier, which had to be replaced. The NATO IIIA was launched on 22 April 1976 [B-44].

P-72-2

The P-72-2 was an experimental satellite that was to be flown as a part of Air Force SSD's Space Test Program (STP). The focus of the P-72-2 was infrared sensor technology; the project was to provide data for the improvement of future systems. Specific objectives were to compare MWIR and SWIR sensor performance and staring mosaic and line scanning sensor technologies using measurements of the same Earth background and targets. The primary payload was the RM-20 sensor experiment. The experiment included two separate IR sensors. The RM-20A was a linescan sensor with two-color capability (MWIR and SWIR), while the RM-20B was a staring mosaic sensor. Secondary payloads included an ultraviolet radiometer, a preliminary aerosol monitor and a wide-band radio signal experiment. The P-72-2 was intended to be a low-cost measurement program with a mission design life of only six months. This is reflected in the sensor design because only passive cooling is used for both the RM-20A and RM-20B. The P-72-2 was to fly in a

400-nautical mile circular orbit at an inclination of 98 degrees. The Atlas F was the launch vehicle [B-45].

Rockwell International was the prime contractor for the P-72-2. Rockwell was also the contractor for the RM-20B. Lockheed's Palo Alto Research Lab was the subcontractor for the RM-20A. The spacecraft contract was awarded to Rockwell in July 1972. The original plan called for first launch in December 1973. Sensor development started with the RM-20A go-ahead in December 1970 and RM-20B go-ahead in August 1971. PDR for both sensors occurred in October 1971. Sensor acceptance testing was complete in April and January 1974. System PDR and CDR occurred in October 1972 and April 1973. Spacecraft acceptance testing started in May 1974 and was completed in March 1975. Delays in acceptance testing of approximately three months were caused by damage inflicted on the RM-20B sensor due to improperly applied voltage, tape drive malfunctions, a transmitter anomaly, a command distributor malfunction, and center-of-gravity problems with the orbit insertion motor. The P-72-2 was launched in April 1975 but failed to achieve orbit due to a launch vehicle failure [B-45 through B-49].

SATELLITE BUSINESS SYSTEMS (SBS)

The SBS was a consortium established by Comsat, IBM, and Aetna Life and Casualty in 1975. The SBS network provides integrated voice and data services to large corporations in the continental United States. The network was unique for its time in that all transmissions used digital on-demand time-division multiple access links. The SBS satellite was the first application of the Hughes HS376 spacecraft bus. With a total of 36 orders, the HS376 is the West's most widely used civil communications platform. Five SBS/HS376 satellites were procured and launched. Like all Hughes spacecraft of the time, the SBS was spin-stabilized with body-mounted solar arrays. The launch vehicle for the first two SBS flights was a Delta 3910 with a PAM-D upper stage; this was the first application of the PAM-D. Satellites three and four were launched by Shuttle/PAM-D. SBS was the first commercial satellite to be launched on the Shuttle. Follow-on SBS satellite 6 uses a more powerful Hughes HS393 bus [B-1 and B-33].

SBS contracted for the development and production of three HS376 satellites in December 1977. The original plan was for an August 1980 first delivery and November 1980 first launch. PDR was accomplished on schedule in April 1978. CDR occurred three months behind schedule in January 1979. Serious delays were associated with the qualification model satellite. Qualification model component fabrication began in April 1978, two months behind schedule. Qualification testing started in April 1979 and was completed in January 1980, seven and ten months behind schedule. Delays for the qualification model did not greatly affect the first flight-model satellite, which was delivered only a month behind schedule in September 1980. Launch was accomplished two weeks behind schedule on November 15. The satellite became operational in March 1981 [B-34].

SPACECRAFT CHARGING AT HIGH ALTITUDES (SCATHA)

The SCATHA was a joint project between the Air Force's STP and NASA's GSFC. The Office of Naval Research also provided experiments for the project. The STP designation for SCATHA was P-78-2. The primary purpose of the mission was to provide spacecraft designers with data on electrostatic charging effects harmful to satellites in high Earth orbits. A total of 13 experiments flew on the single SCATHA spacecraft. The experiments included electron and xenon ion guns to alter spacecraft charging, electric field detectors and instruments to measure damage on the spacecraft's surface caused by charging. Associated with the experiments are antennas up to 300 feet long and five booms, which must be deployed one at a time. The large number of payload boxes and spacecraft appendages made for a difficult spacecraft integration task. Weight limitations of the Delta 2914 launch vehicle meant that much graphite epoxy material was used in the spacecraft's structure. In order to traverse all the altitudes of interest, the SCATHA had an elliptical orbit of 23,355 by 14,880 nautical miles [B-39 and B-49].

The prime contractor for SCATHA was Martin Marietta. The contract was awarded in March 1976. SCATHA development was marked by multiple system PDRs and CDRs and cost growth of 220%. In our database, we use the final PDR and CDR dates. Almost half of the cost growth was attributable to out-of-scope changes in the payloads and experiments. The SCATHA completed acceptance testing in October 1978; this marks satellite delivery in our database. The spacecraft was launched in February 1979 [B-2 and B-3].

TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

The TDRSS provides tracking and data relay capability for telemetry, tracking, and command (TT&C) data and for mission data between satellites in lower Earth orbit (LEO) and a centrally located ground station. There are two active satellites and one on-orbit spare plus a fourth for commercial service. The TDRSS functions as a key player in the Space Shuttle System, providing coverage of data and voice communications via Earth station in a constellation of four geosynchronous satellites and a ground terminal. The four satellites comprising TDRSS are basically identical and interchangeable and are differentiated only by mission and/or purpose. The TDRSS is a highly complex telecommunications satellite that weighs 3,402 pounds dry, has three-axis stabilization, and has a design life of 10 years. TDRSS is owned and operated by the Continental-Telephone (Contel) Space Communications Company. TRW designed, developed, built, and tested TDRSS as a subcontractor to Contel Spacecom. TDRSS has no user signal processing capability on-board. As many functions as possible have been removed from the satellite and based at ground stations to ensure a long life and to allow for more on-board spacecraft communications channels. The TDRSS satellites were launched by the Space Shuttle and Atlas Centaur [B-6].

The TDRSS development began with extensive system definition studies from 1973 through early 1976. In December 1976, the TDRSS development contract was awarded to TRW, the system design review (SDR) was held on February 1977, and the PDR was held on April 1977. The CDR planned for May 1978 was delayed for three months to August 1978. The first satellite was delivered in December 1982 and was launched on the Space Shuttle in April 1983, over three years after the planned launch date [B-50].

Schedule delays in the TDRSS program were due to technical problems with solar arrays and traveling wave tubes. Another delay was due to modifications necessary to avoid jamming by Soviet radar. In the middle of the program, DoD apparently added requirements that lead to added system weight. This meant that the TDRSS had to be modified to be Shuttle-compatible and that the Shuttle had to become operational before TDRSS could be launched [B-6].

VIKING ORBITER

There were two major hardware items associated with each of the two Viking missions, the Viking Orbiter and the Viking Lander. The Viking Orbiter was to deliver the Lander to Mars orbit, survey and select landing sites, relay data from the Lander to Earth and perform observations of the Martian atmosphere and surface. The Viking Lander was to soft-land on Mars and perform experiments to determine the presence of life and collect data on the surface environment; the Lander was the first U.S spacecraft to land on another planet. Most of the scientific experiments for the Viking missions were associated with the Lander. The Orbiter carried only three instruments; an atmospheric water detector, an infrared thermal mapper and two narrow angle television cameras. The entire Orbiter/Lander combination weighed over 5,000 pounds, making it the heaviest planetary system in our data sample. The Viking system also had the highest power requirements with 1,400 watts BOL power at Earth from solar arrays on the Orbiter. The Viking was launched by Titan III with a centaur upper stage [B-1 and B-35].

The overall Viking project was managed at NASA's Langley Research Center while JPL had management responsibility for the Orbiter. Martin Marietta was the prime contractor for the Lander and system integration; JPL was the contractor for the Orbiter. Although the Viking Orbiter was large in comparison to previous JPL spacecraft, the spacecraft's technology and design approach owed much to Mariner experience. The Lander by comparison presented much greater technological risk [B-1 and B-35].

The original Viking plan was to have a first launch in 1973. However the program was realigned in January 1970 because of budget cuts. The new schedule called for first launch to occur in 1975, the next practical launch opportunity. Only a small amount of effort had been expended at the time of the realignment. Martin Marietta had been awarded its contract in October 1969; a stop-work order went into effect in January 1970. The contract was re-negotiated and work on the first option was started in February; this marks program ATP in our database [B-2, B-3, and B-35].

The original plan called for Orbiter PDR in May 1970; the January 1970 revised schedule called for a January 1972 PDR. The milestone was accomplished ahead of schedule in October 1971. Most remaining major milestones were accomplished a little behind schedule. For CDR: original schedule, June 1971; revised schedule, January 1973; accomplished, July 1973. For qualification test completion: original schedule, November 1972; revised schedule, July 1974; accomplished, January 1975. Schedule delays were routine and did not substantially affect flight hardware availability for the 1975 launch [B-35].

One element of the Orbiter program that underwent restructuring was the use of spacecraft. Originally there were to be three full-up spacecraft: VO1, which was to be a dedicated qualification article, and VO2 and VO3, which were to be the Orbiters for the first and second Viking missions. In September 1974, VO1 testing was complete, and VO2 and VO3 testing was underway. At this time all testing of VO3 was ordered to cease as a cost containment measure; the second test team was disbanded and VO3 was put into storage. VO1 was redesignated as a flight unit. The redesignation required more analysis and testing; VO1 was certified for flight in January 1975. VO2 completed testing later that month. VO1 and VO2 were shipped to Kennedy Space Center (KSC) in February, two months after the date proposed in the January 1970 schedule. This marks first delivery in our database. The Viking Lander had arrived at KSC in January. The Orbiter and Lander were first mated in March. The extensive preparations for launch included sterilizing the complete system so that life science experiments aboard the Lander would not be corrupted. The two missions were launched in August and September of 1975 [B-35].

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APPENDIX C

SPACECRAFT GROUND TEST INDICES

APPENDIX C

SPACECRAFT GROUND TEST INDICES

Spacecraft ground testing can be broken down into two major categories, qualification testing and acceptance testing. Within each category, testing is performed at both the system and component level. The general testing approach is to expose components and the total system to specified levels of acoustic, shock, vibration, and thermal stresses while exercising the functions of the component or system. Qualification testing is aimed at validating system and component design, while acceptance testing is oriented toward detecting workmanship problems and minimizing "infant mortality" in production flight hardware. Qualification testing is performed to more rigorous levels than acceptance testing. Air Force MIL-STD-1540B specifies unmanned spacecraft testing requirements. The requirements are listed in Table C-1.

Table C-1. MIL-STD-1540B Test Requirements

	Systems		Components	
	Qualification	Acceptance	Qualification	Acceptance
Functional	Design range performance	Nominal performance	Same as system	
Acoustics	Maximum flight + 6 dB for 3 minutes	Maximum flight for 1 minute	Same as system	
Shock	3 Pyroshock firings	1 Pyroshock firing	3 shocks	1 shock
Random Vibration	—	—	Maximum flight + 6 dB for 3 minutes	Maximum flight for 1 minute
Sinusoidal Vibration	—	—	Each Axis	—
Thermal Cycling	50 cycles, 70° C range, 8 thermal vacuum or	40 cycles, 70° C range, 1 thermal vacuum or	24 cycles, -34° to + 71° C minimum	8 cycles, -24° to + 61° C minimum
Thermal Vacuum	8 cycles, maximum/ minimum temp. +- 10° C	4 cycles, maximum/ minimum temp.	3 cycles, -34° to + 71° C minimum	1 cycle, -24° to + 61° C minimum
Burn-in				10 cycles, 300 hours

The Aerospace Corporation developed an index of MIL-STD-1540B implementation for various DoD satellite programs and commercial contractors.[1] The test thoroughness index rates and weighs each of the system and component tests conducted for each program (or in the case of the commercial systems, each contractor). A score of one indicates complete compliance with MIL-STD-1540B. Index values are included in Table C-2.

Table C-2. MIL-STD-1540B Implementation

	Test Thoroughness Indices		
	Qualification	Acceptance	Composite
DSP 1	0.42	0.49	0.45
DSP 14	0.56	0.99	0.78
DMSP 5D-2	0.46	0.81	0.65
DMSP 5D-1	0.30	0.37	0.34
GPS	0.92	0.92	0.93
DSCS II	0.69	0.53	0.62
DSCS III	—	0.88	0.88
ISAT IV (Hughes)	0.60	0.84	0.73
ISAT V (Ford)	0.67	0.81	0.75
FLTSAT	0.63	0.85	0.75

1 The test thoroughness index is presented in J. Meltzer, O. Hamberg, and W. F. Tosney, *Review of Satellite Testing*, The Aerospace Corporation, ATR-88(8003)-6.

APPENDIX D

ADDITIONAL PREDICTION ERROR SUMMARY TABLES

Table D-1. Equation 8.0 Prediction Error Summary

Spacecraft program	Manufacturing milestone	Delay dummy variable: delay=1, 0 otherwise	Cumulative spacecraft quantity	Actual months from milestone to test complete	Predicted months from milestone to test complete	Error (Actual -Pred.)	Multiplicative residual (Actual/ Predicted)
DMSP 5D-1	STest	0	2	24	13.5	10.5	1.78
DMSP 5D-1	STest	0	3	14	12.8	1.2	1.09
DMSP 5D-1	STest	0	4	11	12.4	-1.4	.89
DMSP 5D-2	STest	0	1	30	23.9	6.1	1.26
DMSP 5D-2	STest	0	2	31	22.0	9.0	1.41
DMSP 5D-2	STest	0	3	24	20.9	3.1	1.15
DMSP 5D-2	STest	0	4	28	20.2	7.8	1.39
DMSP 5D-2	STest	1	5	43	29.8	13.2	1.44
DMSP 5D-2	STest	0	7	33	18.9	14.1	1.75
DMSP 5D-2	STest	0	8	32	18.6	13.4	1.72
DMSP 5D-2	STest	0	9	30	18.3	11.7	1.64
DSCS III	CAss	0	3	12	9.3	2.7	1.29
DSCS III	CAss	0	4	13	9.0	4.0	1.45
DSCS III	CAss	0	5	6	8.8	-2.8	.69
DSCS III	CAss	0	6	10	8.6	1.4	1.17
DSCS III	CAss	1	8	7	12.5	-5.5	.56
DSCS III	CAss	0	9	8	8.2	-.2	.98
DSCS III	CAss	0	10	9	8.1	.9	1.12
DSCS III	CAss	0	11	11	8.0	3.0	1.38
DSCS III	CAss	0	12	10	7.9	2.1	1.27
DSCS III	CAss	0	13	9	7.8	1.2	1.15
DSCS III	CAss	0	14	6	7.7	-1.7	.78
DSCS III	CAss	0	15	3	7.7	-4.7	.39
DSCS III	SAss	0	3	27	21.7	5.3	1.25
DSCS III	SAss	0	4	26	20.9	5.1	1.24
DSCS III	SAss	0	5	18	20.4	-2.4	.88
DSCS III	SAss	0	6	21	19.9	1.1	1.05
DSCS III	SAss	0	7	29	19.6	9.4	1.48
DSCS III	SAss	1	8	25	29.2	-4.2	.86
DSCS III	SAss	0	9	21	19.0	2.0	1.11
DSCS III	SAss	0	10	20	18.7	1.3	1.07
DSCS III	SAss	0	11	22	18.5	3.5	1.19
DSCS III	SAss	0	12	21	18.3	2.7	1.15
DSCS III	SAss	0	13	22	18.2	3.8	1.21
DSCS III	SAss	0	14	19	18.0	1.0	1.06
DSCS III	SAss	0	15	23	17.9	5.1	1.29
DSCS III	SFab	0	2	32	35.7	-3.7	.90
DSCS III	SFab	0	3	42	34.0	8.0	1.23
DSCS III	SFab	0	4	35	32.9	2.1	1.06
DSCS III	SFab	0	7	34	30.7	3.3	1.11
DSCS III	SFab	1	8	44	45.8	-1.8	.96
DSCS III	SFab	0	9	35	29.8	5.2	1.17
DSCS III	SFab	0	10	27	29.4	-2.4	.92
DSCS III	SFab	0	11	31	29.1	1.9	1.06
DSCS III	STest	0	2	10	13.8	-3.8	.73
DSCS III	STest	0	3	12	13.1	-1.1	.92

Table D-1. Equation 8.0 Prediction Error Summary (continued)

Spacecraft program	Manufac-turing milestone	Delay dummy variable: delay=1, 0 otherwise	Cumulative spacecraft quantity	Actual months from milestone to test complete	Predicted months from milestone to test complete	Error (Actual -Pred.)	Multiplica-tive residual (Actual/ Predicted)
DSCS III	STest	0	4	13	12.7	.3	1.03
DSCS III	STest	0	5	6	12.3	-6.3	.49
DSCS III	STest	0	6	10	12.1	-2.1	.83
DSCS III	STest	0	7	15	11.8	3.2	1.27
DSCS III	STest	1	8	7	17.6	-10.6	.40
DSCS III	STest	0	9	8	11.5	-3.5	.70
DSCS III	STest	0	10	9	11.3	-2.3	.79
DSCS III	STest	0	11	11	11.2	-.2	.98
DSCS III	STest	0	12	10	11.1	-1.1	.90
DSCS III	STest	0	13	9	11.0	-2.0	.82
DSCS III	STest	0	14	6	10.9	-4.9	.55
DSCS III	STest	0	15	3	10.8	-7.8	.28
DSP 1	STest	0	2	9	12.2	-3.2	.74
DSP 1	STest	1	3	12	17.6	-5.6	.68
DSP 1	STest	0	4	9	11.2	-2.2	.80
DSP 1	STest	0	5	6	10.9	-4.9	.55
DSP 14	CAss	0	1	13	17.6	-4.6	.74
DSP 14	CAss	1	2	38	24.5	13.5	1.55
DSP 14	CAss	0	3	23	15.4	7.6	1.49
DSP 14	SAss	0	1	40	40.9	-.9	.98
DSP 14	SAss	1	2	51	57.0	-6.0	.89
DSP 14	SAss	0	3	39	35.8	3.2	1.09
DSP 14	SFab	0	1	70	64.2	5.8	1.09
DSP 14	SFab	1	2	81	89.5	-8.5	.90
DSP 14	STest	0	1	15	24.7	-9.7	.61
DSP 14	STest	1	2	38	34.5	3.5	1.10
DSP 14	STest	0	3	23	21.7	1.3	1.06
FLTSAT	CAss	0	2	7	11.5	-4.5	.61
FLTSAT	CAss	1	3	16	16.5	-.5	.97
FLTSAT	CAss	0	4	10	10.5	-.5	.95
FLTSAT	CAss	0	5	7	10.3	-3.3	.68
FLTSAT	SAss	0	2	12	26.7	-14.7	.45
FLTSAT	SAss	1	3	26	38.5	-12.5	.68
FLTSAT	SAss	0	4	22	24.5	-2.5	.90
FLTSAT	SAss	0	5	9	23.9	-14.9	.38
FLTSAT	SFab	0	2	27	41.9	-14.9	.64
FLTSAT	SFab	1	3	35	60.5	-25.5	.58
FLTSAT	SFab	0	4	34	38.6	-4.6	.88
FLTSAT	SFab	0	5	23	37.5	-14.5	.61
FLTSAT	SFab	0	6	31	36.7	-5.7	.84
FLTSAT	STest	0	2	16	16.1	-.1	.99
FLTSAT	STest	1	3	26	23.3	2.7	1.12
FLTSAT	STest	0	4	22	14.8	7.2	1.48
FLTSAT	STest	0	5	12	14.5	-2.5	.83
FLTSAT	STest	0	6	16	14.1	1.9	1.13
GPS II	CAss	0	2	15	14.3	.7	1.05

Table D-1. Equation 8.0 Prediction Error Summary (continued)

Spacecraft program	Manufac-turing milestone	Delay dummy variable: delay=1, 0 otherwise	Cumulative spacecraft quantity	Actual months from milestone to test complete	Predicted months from milestone to test complete	Error (Actual -Pred.)	Multiplica-tive residual (Actual/ Predicted)
GPS II	CAss	0	3	9	13.6	-4.6	.66
GPS II	CAss	0	4	12	13.1	-1.1	.91
GPS II	CAss	0	5	11	12.8	-1.8	.86
GPS II	CAss	1	6	25	19.0	6.0	1.32
GPS II	CAss	0	7	10	12.3	-2.3	.81
GPS II	SAss	0	2	31	33.2	-2.2	.93
GPS II	STest	0	2	15	20.1	-5.1	.75
GPS II	STest	0	3	8	19.1	-11.1	.42
GPS II	STest	0	4	10	18.5	-8.5	.54
GPS II	STest	0	5	11	18.0	-7.0	.61
GPS II	STest	1	6	25	26.7	-1.7	.94
GPS II	STest	0	7	10	17.3	-7.3	.58
NATO III	CAss	0	2	5	6.8	-1.8	.74
NATO III	CAss	0	3	6	6.4	-.4	.93
NATO III	CAss	0	4	5	6.2	-1.2	.80
NATO III	SAss	0	2	10	15.7	-5.7	.64
NATO III	SAss	0	4	9	14.5	-5.5	.62
NATO III	STest	0	2	5	9.5	-4.5	.53
NATO III	STest	0	3	6	9.1	-3.1	.66
NATO III	STest	0	4	5	8.8	-3.8	.57
TDRSS	SFab	0	2	61	49.5	11.5	1.23
TDRSS	STest	0	2	41	19.0	22.0	2.15
TDRSS	STest	1	3	58	27.5	30.5	2.11
TDRSS	STest	0	4	25	17.5	7.5	1.43
TDRSS	STest	0	5	30	17.1	12.9	1.76
TDRSS	STest	0	6	24	16.7	7.3	1.44
TDRSS	STest	0	7	24	16.4	7.6	1.46

Notes: SFab=Start Component Fabrication, SAss= Start System Assembly, CAss=Complete System Assembley, STest= System test start,

Table D-2. Equation 9.0 Prediction Error Summary

Program Type	Software Type	Environment	Actual Value (months)	Predicted Value (months)	Error (Actual -Pred.)	Multiplicative Residual (Actual/ Pred.)
Earth-Orbiting Sensor	Application	Ground	6.1	12.0	-5.9	0.51
Earth-Orbiting Sensor	Application	Ground	6.6	10.7	-4.1	0.62
Earth-Orbiting Sensor	Application	Ground	6.6	11.7	-5.1	0.56
Earth-Orbiting Sensor	Application	Ground	15.3	14.4	0.9	1.06
Earth-Orbiting Sensor	Application	Ground	15.3	16.6	-1.3	0.92
Earth-Orbiting Sensor	Application	Ground	15.3	18.6	-3.3	0.82
Earth-Orbiting Sensor	Application	Ground	15.3	14.4	0.9	1.06
Earth-Orbiting Sensor	Support	Ground	15.3	18.7	-3.4	0.82
Earth-Orbiting Sensor	Application	Ground	15.3	21.0	-5.7	0.73
Earth-Orbiting Sensor	Application	Ground	18.7	21.7	-3.0	0.86
Earth-Orbiting Sensor	Application	Ground	18.7	22.5	-3.8	0.83
Earth-Orbiting Sensor	Application	Ground	22.2	24.6	-2.4	0.90
Earth-Orbiting Sensor	Support	Ground	23.0	27.7	-4.7	0.83
Earth-Orbiting Sensor	Application	Ground	30.1	26.9	3.2	1.12
Earth-Orbiting Sensor	Support	Ground	30.1	29.0	1.1	1.04
Earth-Orbiting Sensor	Support	Ground	30.1	27.3	2.8	1.10
Earth-Orbiting Sensor	Support	Ground	30.1	28.3	1.8	1.06
Earth-Orbiting Sensor	Support	Ground	30.1	27.7	2.4	1.09
Earth-Orbiting Sensor	Support	Ground	30.1	30.3	-0.2	0.99
Earth-Orbiting Sensor	Application	Ground	37.1	43.0	-5.9	0.86
Earth-Orbiting Sensor	Application	Ground	37.1	37.2	-0.1	1.00
Earth-Orbiting Sensor	Application	Space	44.1	39.9	4.2	1.11
Earth-Orbiting Sensor	System	Space	44.1	59.2	-15.1	0.74
Earth-Orbiting Sensor	Application	Space	44.1	39.6	4.5	1.11
Earth-Orbiting Sensor	Application	Space	44.1	43.4	0.7	1.02
Earth-Orbiting Sensor	Application	Ground	47.1	35.7	11.4	1.32
Manned Spacecraft	System	Ground	19.0	16.2	2.8	1.18
Manned Spacecraft	System	Ground	23.0	58.6	-35.6	0.39
Manned Spacecraft	System	Ground	30.0	24.3	5.7	1.23
Manned Spacecraft	System	Ground	31.1	74.3	-43.2	0.42
Manned Spacecraft	System	Space	35.5	46.0	-10.5	0.77
Manned Spacecraft	Application	Ground	47.1	43.7	3.4	1.08
Manned Spacecraft	System	Ground	52.0	33.2	18.8	1.57
Manned Spacecraft	System	Ground	53.1	78.5	-25.4	0.68
Manned Spacecraft	System	Ground	60.0	34.5	25.5	1.74
Manned Spacecraft	System	Ground	72.1	35.4	36.7	2.04
Manned Spacecraft	Application	Ground	75.1	62.3	12.8	1.21
Manned Spacecraft	System	Ground	143.2	108.2	35.0	1.32
Planetary	Support	Ground	24.0	30.4	-6.4	0.79
Planetary	Application	Ground	24.0	31.0	-7.0	0.77
Planetary	Application	Ground	24.0	45.4	-21.4	0.53
Planetary	Application	Ground	36.1	58.7	-22.6	0.61
Planetary	Application	Ground	36.1	97.8	-61.7	0.37

Table D-2. Equation 9.0 Prediction Error Summary (continued)

Program Type	Software Type	Environment	Actual Value (months)	Predicted Value (months)	Error (Actual -Pred.)	Multiplicative Residual (Actual/ Pred.)
Planetary	Application	Ground	48.1	23.6	24.5	2.04
Planetary	Application	Ground	48.1	58.0	-9.9	0.83
Planetary	Application	Ground	48.3	39.6	8.7	1.22
Planetary	Application	Ground	72.1	66.4	5.7	1.09
Planetary	Application	Ground	96.1	72.1	24.0	1.33
Planetary	Application	Ground	96.1	109.8	-13.7	0.87
Planetary	Support	Ground	96.1	79.9	16.2	1.20
Planetary	Application	Ground	117.1	125.7	-8.6	0.93

Table D-3. Equation 9.1 Prediction Error Summary

Program Type	Software Type	Environment	Actual Value (months)	Predicted Value (months)	Error (Actual -Pred.)	Multiplicative Residual (Actual/ Pred.)
Earth-Orbiting Sensor	Application	Ground	6.1	12.0	-5.9	0.51
Earth-Orbiting Sensor	Application	Ground	6.6	10.7	-4.1	0.62
Earth-Orbiting Sensor	Application	Ground	6.6	11.7	-5.1	0.56
Earth-Orbiting Sensor	Application	Ground	15.3	14.4	0.9	1.06
Earth-Orbiting Sensor	Application	Ground	15.3	16.6	-1.3	0.92
Earth-Orbiting Sensor	Application	Ground	15.3	18.6	-3.3	0.82
Earth-Orbiting Sensor	Application	Ground	15.3	14.4	0.9	1.06
Earth-Orbiting Sensor	Support	Ground	15.3	18.7	-3.4	0.82
Earth-Orbiting Sensor	Application	Ground	15.3	21.0	-5.7	0.73
Earth-Orbiting Sensor	Application	Ground	18.7	21.7	-3.0	0.86
Earth-Orbiting Sensor	Application	Ground	18.7	22.5	-3.8	0.83
Earth-Orbiting Sensor	Application	Ground	22.2	24.6	-2.4	0.90
Earth-Orbiting Sensor	Support	Ground	23.0	27.7	-4.7	0.83
Earth-Orbiting Sensor	Application	Ground	30.1	26.9	3.2	1.12
Earth-Orbiting Sensor	Support	Ground	30.1	29.0	1.1	1.04
Earth-Orbiting Sensor	Support	Ground	30.1	27.3	2.8	1.10
Earth-Orbiting Sensor	Support	Ground	30.1	28.3	1.8	1.06
Earth-Orbiting Sensor	Support	Ground	30.1	27.7	2.4	1.09
Earth-Orbiting Sensor	Support	Ground	30.1	30.3	-0.2	0.99
Earth-Orbiting Sensor	Application	Ground	37.1	43.0	-5.9	0.86
Earth-Orbiting Sensor	Application	Ground	37.1	37.2	-0.1	1.00
Earth-Orbiting Sensor	Application	Space	44.1	39.9	4.2	1.11
Earth-Orbiting Sensor	System	Space	44.1	59.2	-15.1	0.74
Earth-Orbiting Sensor	Application	Space	44.1	39.6	4.5	1.11
Earth-Orbiting Sensor	Application	Space	44.1	43.4	0.7	1.02
Earth-Orbiting Sensor	Application	Ground	47.1	35.7	11.4	1.32
Manned Spacecraft	System	Ground	19.0	16.2	2.8	1.18

Table D-2. Equation 9.1 Prediction Error Summary (continued)

Program Type	Software Type	Environment	Actual Value (months)	Predicted Value (months)	Error (Actual -Pred.)	Multiplicative Residual (Actual/ Pred.)
Manned Spacecraft	System	Ground	23.0	58.6	-35.6	0.39
Manned Spacecraft	System	Ground	30.0	24.3	5.7	1.23
Manned Spacecraft	System	Ground	31.1	74.3	-43.2	0.42
Manned Spacecraft	System	Space	35.5	46.0	-10.5	0.77
Manned Spacecraft	Application	Ground	47.1	43.7	3.4	1.08
Manned Spacecraft	System	Ground	52.0	33.2	18.8	1.57
Manned Spacecraft	System	Ground	53.1	78.5	-25.4	0.68
Manned Spacecraft	System	Ground	60.0	34.5	25.5	1.74
Manned Spacecraft	System	Ground	72.1	35.4	36.7	2.04
Manned Spacecraft	Application	Ground	75.1	62.3	12.8	1.21
Planetary	Support	Ground	24.0	30.4	-6.4	0.79
Planetary	Application	Ground	24.0	31.0	-7.0	0.77
Planetary	Application	Ground	24.0	45.4	-21.4	0.53
Planetary	Application	Ground	36.1	58.7	-22.6	0.61
Planetary	Application	Ground	48.1	23.6	24.5	2.04
Planetary	Application	Ground	48.1	58.0	-9.9	0.83
Planetary	Application	Ground	48.3	39.6	8.7	1.22
Planetary	Application	Ground	72.1	66.4	5.7	1.09
Planetary	Application	Ground	96.1	72.1	24.0	1.33
Planetary	Application	Ground	96.1	109.8	-13.7	0.87
Planetary	Support	Ground	96.1	79.9	16.2	1.20
Planetary	Application	Ground	117.1	125.7	-8.6	0.93

APPENDIX E

LOGIT ANALYSIS OF MANUFACTURING DELAYS

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In the example application in Chapter V, we implemented the DELAY dummy variable through a static probability measure. The measure was simply the number of delayed spacecraft units divided by the total number of units in the data sample. Another approach is to explicitly model the probability of a manufacturing delay as a function of some attribute in the data. As most of the delayed spacecraft units were in the early part of a production run, we modeled the probability of a manufacturing delay as a function of flight-model spacecraft cumulative quantity. We did this using a binary logit model.

The dependent variable in a binary logit model is a 1/0 dummy variable; in our case the DELAY variable plays this role. In the logit model the probability of a delay for the nth observation is expressed as

$$P_n(i) = 1/(1+ \exp[-(\alpha+\beta x_n)]),$$

where α and β are the model parameters and x_n is the attribute measure for the nth observation. The probability of a delay not occurring is expressed as

$$P_n(j) = \exp[-(\alpha+\beta x_n)]/(1+ \exp[-(\alpha+\beta x_n)]),$$

where $P_n(i) + P_n(j) = 1$

In terms of our data, $P_n(i)$ is the probability that $DELAY_n=1$ and $P_n(j)$ the probability that $DELAY_n=0$. The maximum likelihood estimators for α and β can be found by maximizing the log likelihood function:

$$\sum [(DELAY_n) \log(P_n(i)) + (1-DELAY_n) \log(P_n(j))],$$

where the sum of the log likelihood functions for each individual observation is taken over all n observations.

In our model x_n is the natural logarithm of flight-model spacecraft cumulative quantity (lnCumQ). Data characterizing lnCumQ and DELAY were available for 43 spacecraft units. We employed the data and a nonlinear optimization algorithm to calculate the values of α and ß that maximize the log likelihood function. The resulting probability relationship is:

$$P(DELAY=1) = 1/(1+\exp[-(.1505 - 1.361(\ln CumQ))]),$$

where the coefficient on lnCumQ is significant at the .12 level. We plot the relationship in Figure E-1.

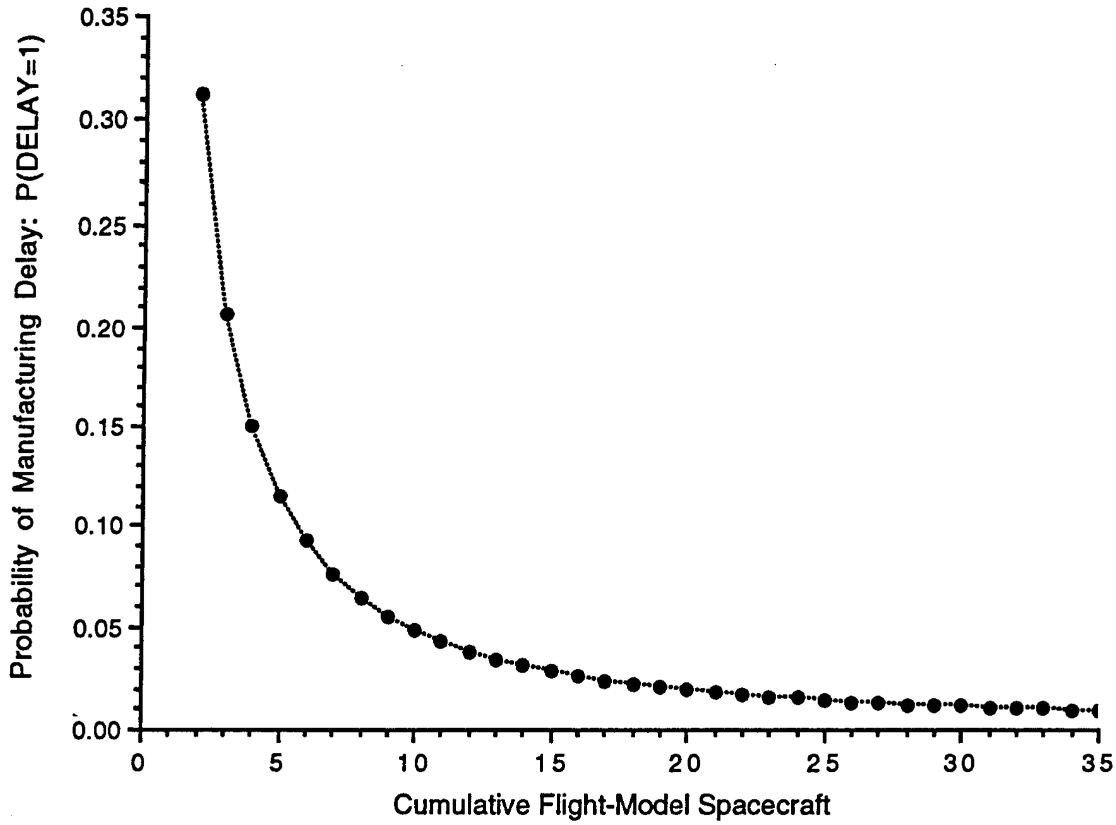

Figure E-1. Probability of a Spacecraft Manufacturing Delay as a Function of Cumulative Quantity.

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REFERENCES

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ABBREVIATIONS

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AE-C	Atmospheric Explorer C
AEDC	Arnold Engineering Development Center
AEM-HCMM	Application Explorer Mission-Heat Capacity Mapping mission
BAF	balance-adjustment factor
BMDO	Ballistic Missile Defense Organization
BOl	beginning of life
CDR	critical design review
CRO	Gamma Ray Observatory
D*V	demonstration and validation
DTV	development test vehicle
EHF	extremely high frequency
EOL	end of life
EPS	electrical power system
FSD	full-scale development
GE	General Electric
GFE	government-furnished equipment
GSFC	Goddard Space Flight Center
HCMR	heat capacity mapping radiometer
HdCdTe	mercury cadmium telluride
HEAO	High Energy Astronomy Observatory
HST	Hubble Space Telescope
I&T	integration and text
IDCSP	Initial Defense Communications Systems Program
IPTO	initial power turn-on
ISAT	International Telecommunications Spacecraft System
ITT	International Telephone and Telegraph
kg	kilograms
km	kilometers
KSC	Kennedy Space Center
KSLOC	thousands of source lines of code
lbs	pounds

LEO	lower earth orbit
LEP	life extension program
MDM	mission data message
MHz	megahertz
NATO	North Atlantic Treaty Organization
nmi	nautical miles
OLS	Operational Linescan System
ORU	orbital replacement units
OTA	Optical Telescope Assembly
PbS	lead sulfide
PDR	preliminary design review
PRNSA	Pseudo-Random Noise Signal Assembly
PTM	proof-test model
QTV	qualification test vehicle
RFP	request for proposals
SAF	spacecraft assembly facility
SBS	Space Business Systems
SCATHA	Spacecraft Charging at High Altitudes
SDR	system design review
SDR	system design review
SDTP	Space Test Program
SED	system evolutionary design
SEE	standard error of the estimate
SI	Scientific Instruments
SSCAG	Space System Cost Analysis Group
SSM	Support System Module
STP	Space Test Program
TT&C	telemetry, tracking and command
USAF	United States Air Force
WEC	Westinghouse Electric Company